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A COMPUTER AIDED METHOD FOR THE MEASUREMENT OF
FIBER DIAMETERS BY LASER DIFFRACTION

by

Mark Gerald Storch

September 1986

Thesis Advisor:

Professor Edward M. Wu

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A Computer Aided Method for the Measurement of
Fiber Diameters by Laser Diffraction

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN AERONAUTICAL ENGINEERING

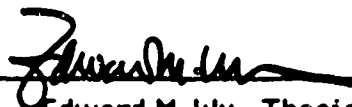
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ABSTRACT

This thesis investigates the computer aided measurement of fiber diameters by laser diffraction. The proposed system consists of a light sensitive Random Access Memory (RAM) chip which collects light intensity data from the laser diffraction pattern. Measurements of the spatial location of the nodes of the diffraction pattern enables the calculation of the fiber diameter. These measurements may be performed manually which is tedious and requires subjective judgement of the nodes. The alternative method of direct processing of the intensity pattern was investigated. Simulation is conducted to examine the feasibility of this method. Results show such a system to be capable of providing one order of magnitude greater accuracy than optical microscopy measurements (with a shearing eyepiece) and double the accuracy of manual laser diffraction methods with the added advantage of permitting the option of total computer automation in data interpretation.



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LIST OF SYMBOLS

α	Argument of the Bessel Functions
a	Width of a slit in Fraunhofer diffraction theory
b_n	Bessel coefficient ($J_n/H_n^{(2)}$)
d	Diameter of a fiber
θ	Angular position in diffraction pattern (radians)
J_n	Bessel function of the first kind
$H_n^{(2)}$	Hankel function of the second kind
I_{TR}	Threshold Intensity Ratio
K_o	Constant associated with the real fiber intensity equation
λ	Wavelength of laser (632.8 nm for He-Ne)
L	Longitudinal position defining distance from fiber to diffraction pattern
m	Integer indicating interference node number
P	Geometric center of diffraction pattern
Δx	Width of Micron Eye array (approximately 4.4 mm)
x	Lateral position in diffraction pattern (perpendicular to laser beam)
Y_n	Bessel function of the second kind

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I. INTRODUCTION

Fiber reinforced composites are replacing structural metal components in today's aircraft. The high strength and reduced weight of composites results in less drag, increased payload, and longer fatigue life. Additionally, the directional properties of composite materials provide unique design advantages over conventional materials.

As with many developing technologies, the reasons for the success of fiber composites was not initially appreciated. Tsai [Ref. 1:p. 2] states that fortunately the modern composite was so strong it was reliable and competitive in spite of less than optimum design practice. Over the last twenty years, much progress has been made in understanding the micro and macro mechanics of composite materials. As this knowledge matures and is incorporated into the design process, the full potential of these materials can be realized.

An important contribution to the design process is modeling structural reliability. Development of probabilistic models for a composite must take into account the complex relationships that exist between fiber and matrix.

One important parameter in the probabilistic model is fiber diameter, since variations in fiber diameter affect fiber failure density. Therefore, more accurate fiber diameter measurement results in an enhanced reliability model and a more quantitative prediction of structural reliability.

The purpose of this research is to investigate a computer aided method of fiber diameter measurement. The existing procedure of diameter measurement by laser diffraction is accurate to within 0.5% [Ref. 2:p. 210]. It is desired to improve this accuracy by interpreting the diffraction pattern with a light sensitive RAM chip.

The presentation begins with a discussion of diffraction pattern analysis. This is followed by an introduction to the Micron Eye's theory and operation. Next, the simulation is discussed in depth followed by the results and conclusions.

II. BACKGROUND

Fiber diameter measurement by laser diffraction is conducted by obstructing a collimated laser beam with a fiber sample. A diffraction pattern results and is characterized by alternating maxima and minima symmetric about a central maximum. (See Figure 1)

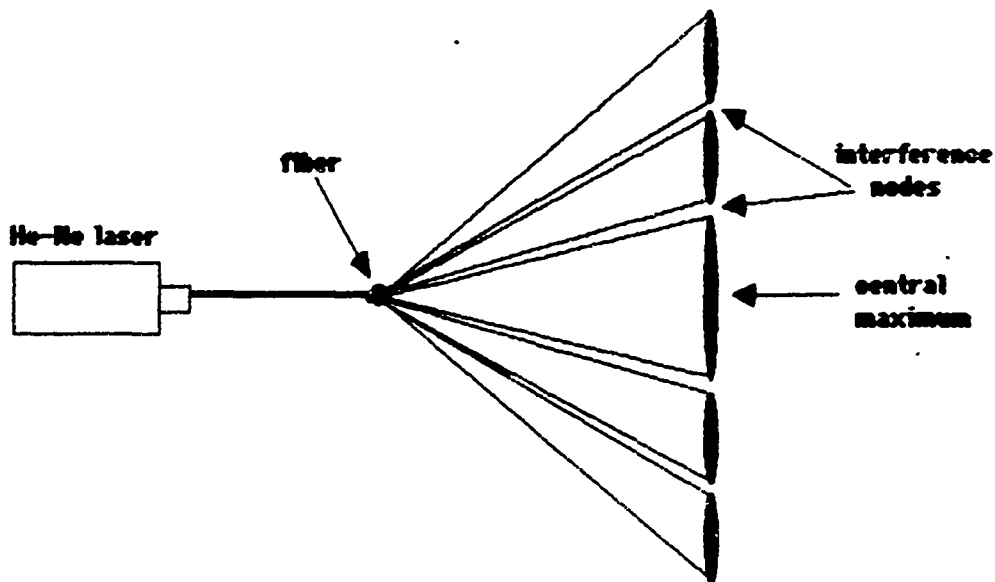


Figure 1. Fiber Diameter Measurement by Laser Diffraction

In previous work, Perry, Ineichen, and Eliasson, [Ref. 3] and Bennett, [Ref. 4], interpretation of the diffraction pattern consisted of finding the distance between interference nodes (minima). This distance is related to the fiber diameter.

Bennett used the slit approximation (Appendix A) to relate the distance between nodes to the fiber diameter. Perry, et al., introduced a more exact solution by Kerker, [Ref 5:p. 260] and compared it to the slit approximation. Perry, et al., concluded that the slit approximation should be treated with caution. Therefore, Kerker's solution has been adopted for this study.

In his paper, Bennett successfully demonstrated the feasibility of using the light sensitive RAM chip for diameter measurements [Ref 4]. An IS32 OPTICRAM MICRON EYE, manufactured by Micron Technology, Inc., was connected as a peripheral device to an Apple II+ computer. By positioning the Micron Eye so that two interference nodes fit on its surface (see Figure 2), an "exposure" of the diffraction pattern could be printed by the computer (see Figure 3). Analysis of the printed diffraction pattern gave the diameter of the fiber using the slit approximation of Fraunhofer diffraction theory (see Appendix A).



Figure 2. Micron Eye Array with Two Interference Nodes

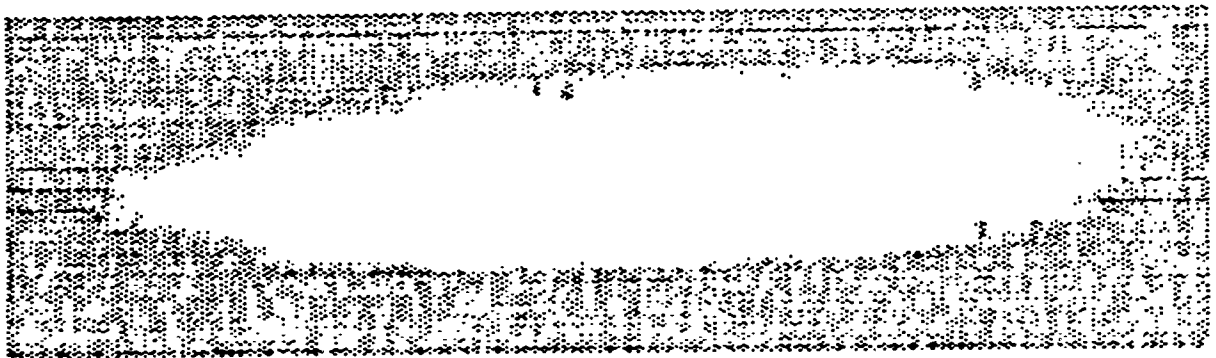


Figure 3. Typical Micron Eye Photograph of Interference Nodes

III. DIFFRACTION PATTERN ANALYSIS

Measuring fiber diameters by laser diffraction, requires an understanding of the diffraction pattern. This chapter introduces some features of diffraction patterns which will be useful in later analysis.

A. FUNCTIONAL DESCRIPTION OF THE DIFFRACTION PATTERN

The diffraction pattern of a fiber can be described as follows:

$$I/I_0 = (2/K_0 L \pi) \left| b_0 + 2 \sum b_n \cos(n\theta) \right|^2 \quad (1)$$

where θ = the scattering angle

$$K_0 = 2\pi / \lambda \quad (\lambda = \text{laser wavelength})$$

$$b_n = J_n(\alpha) / H_n^{(2)}(\alpha)$$

$$\text{and } \alpha = \pi d_f / \lambda \quad (d_f = \text{fiber diameter})$$

$J_n(\alpha)$ are Bessel functions of the first kind,

$H_n^{(2)}(\alpha)$ are Hankel functions of the second kind.

A formal introduction of equation (1) and the related Fraunhofer diffraction theory is presented in Appendix A.

Figure 4 depicts the three dimensional nature of the diffraction pattern. Equation (1) describes the intensities along one linear position, or slice, of the three dimension pattern.

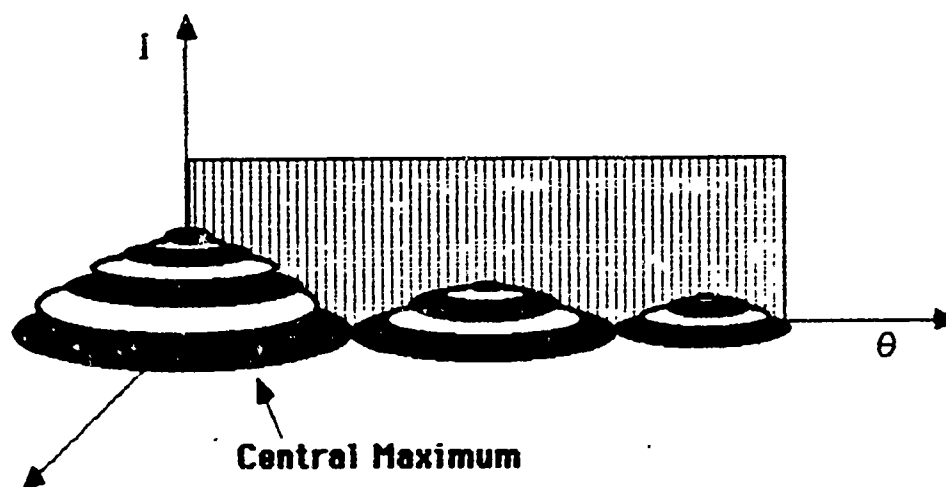


Figure 4. Three Dimensional Diffraction Pattern

A plot of equation (1) is the Intensity Profile which shows the Intensity Ratio (I/I_0) versus the angle theta, for a given fiber diameter and a given fiber to screen distance L . Figure 5 shows a typical Intensity Profile for a fiber diameter of 6.5 microns.

INTENSITY PROFILE

TYPICAL

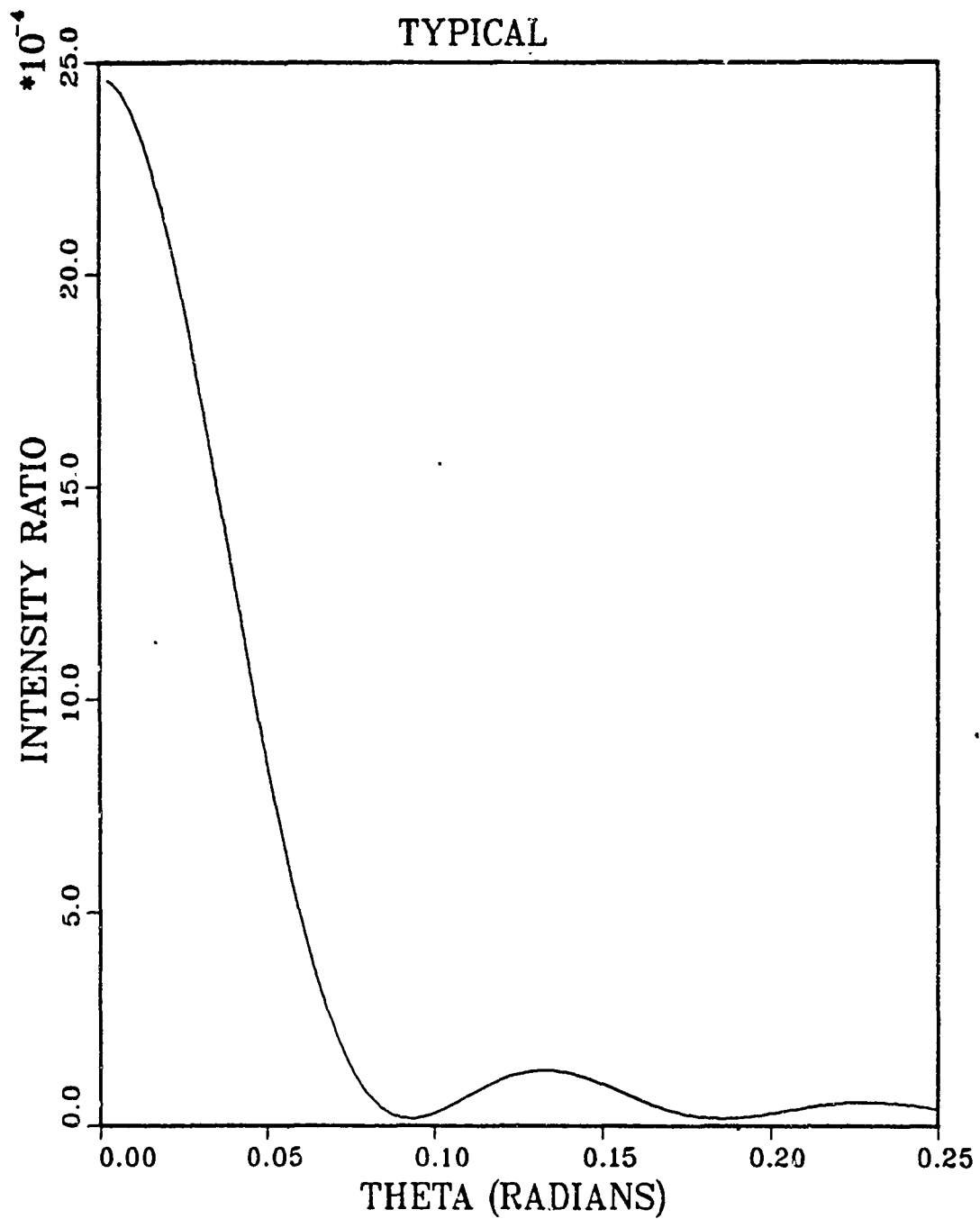


Figure 5. Typical Intensity Profile

B. FEATURES OF THE INTENSITY PROFILE CURVES

The intensity profile has several features worth noting. The first is the central (or zeroth order) maximum. The central maximum is the largest peak in Figure 5 and it is many times more intense than the subsequent maxima. It should also be obvious that the profile is symmetric about the central maximum.

Other features of the curves are shown in Figure 6. Figure 6 is an enlarged view of one of the higher order maxima and associated minima. As discussed in Appendix A, the higher order maxima are not centrally located between the minima, rather they are displaced slightly towards the central maximum. Therefore, the higher order peaks are asymmetric about their maxima. This asymmetry means the maximum derivative on the upslope side of the curve will be greater than the maximum derivative on the downslope side of the curve. This difference is dealt with later when tuning for the optimum exposure is discussed.

The minima in Figure 6 are also distinctive features of the curves. In Appendix A, it is shown that the location of the minima are explicitly related to the diameter of the fiber using the slit approximation:

$$\theta_{\min} = \sin [m\lambda/d] \quad \begin{array}{l} m = \# \text{ of interference node} \\ \lambda = \text{laser wavelength} \\ d = \text{diameter of fiber} \end{array} \quad (2)$$

INTENSITY PROFILE (PERFECT DATA)

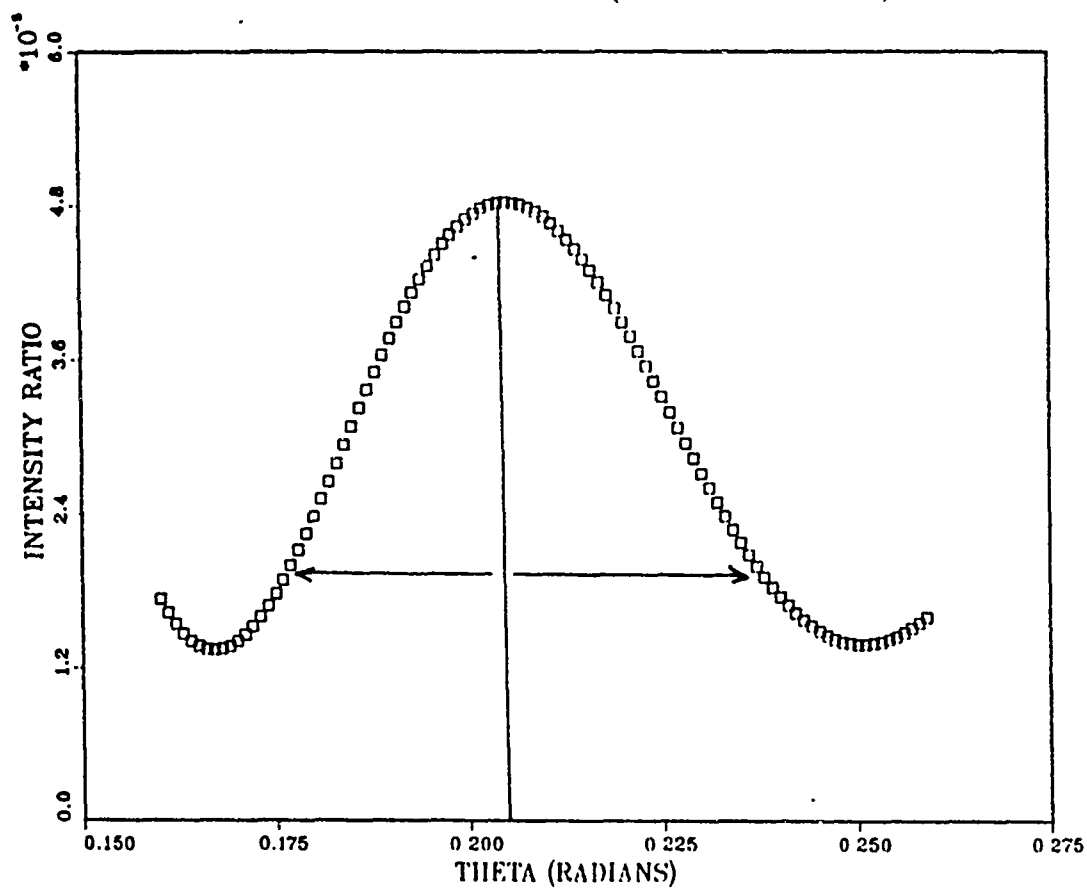


Figure 6. Features of the Intensity Profile Curve

Equation (2) is only an approximation for a fiber, but it is useful for preliminary analysis. Such analysis includes:

- (1) determining where to place the Micron Eye for data collection and,
- (2) providing an initial guess of fiber diameter from diffraction pattern data.

C. EFFECT OF DIAMETER ON THE INTENSITY PROFILE CURVES

Figure 7 shows the effect of diameter on the Intensity Profiles. Note that successive maxima and minima are further from the central maximum for fibers of smaller diameter. This behavior will be important to later analysis.

D. THE MAXIMUM DERIVATIVE AND THE MINIMUM NUMBER OF POINTS

The goal of automated fiber diameter measurement is to find the diameter rapidly and accurately. Speed and accuracy can be exclusive. One can imagine that collecting all the points on the Intensity Profile curve will result in an almost exact determination of fiber diameter, at the expense of time. Two questions must be answered. First, what is the minimum number of points to uniquely describe an intensity profile? Second, where on the curve should these points be obtained?

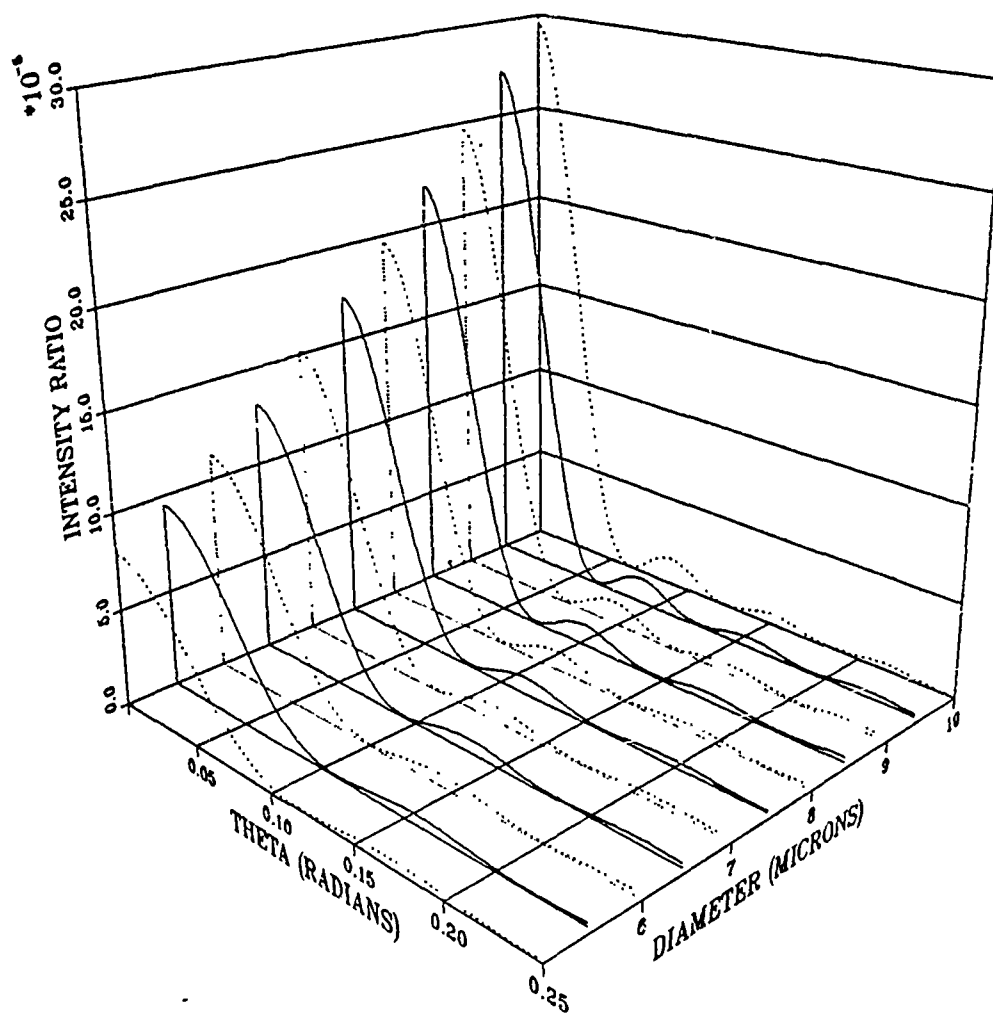


Figure 7. Effect of Diameter on Intensity Profiles (3-D)

1. Minimum Number of Points

Equation (1) consists of an infinite series. Determining the minimum number of points to uniquely define an infinite series is not a straightforward procedure. cursory inspection of Figure 8 leads to the conclusion that one point will not uniquely define the curve, since intensity curves for many diameters pass through the same point (e.g., at $\theta = .04$ radians). If the absolute intensity is not known, 2 points will not provide a unique solution either. For the case of non-absolute intensity measurements (as is the case in this experimental set-up) 3 points appears to uniquely define a curve.

The curve in Figure 9 illustrates this observation. An imaginary line is fixed through three points (i.e., the experimental measurements). The absolute intensities of these three points are not known, and neither are the absolute spatial locations with respect to the central maximum (i.e., θ). Only the relative spatial locations among these points are known. Iteration of the diameter is equivalent to moving this line (with the x marks fixed relative to each other) along different locations on the curve, trying to match all three points. This iteration can be repeated on curves of different diameters (Figures 10 and 11) and no other match can be found. Thus, this argument defines three points as the minimum required to uniquely determine the intensity profile curve.

INTENSITY PROFILE

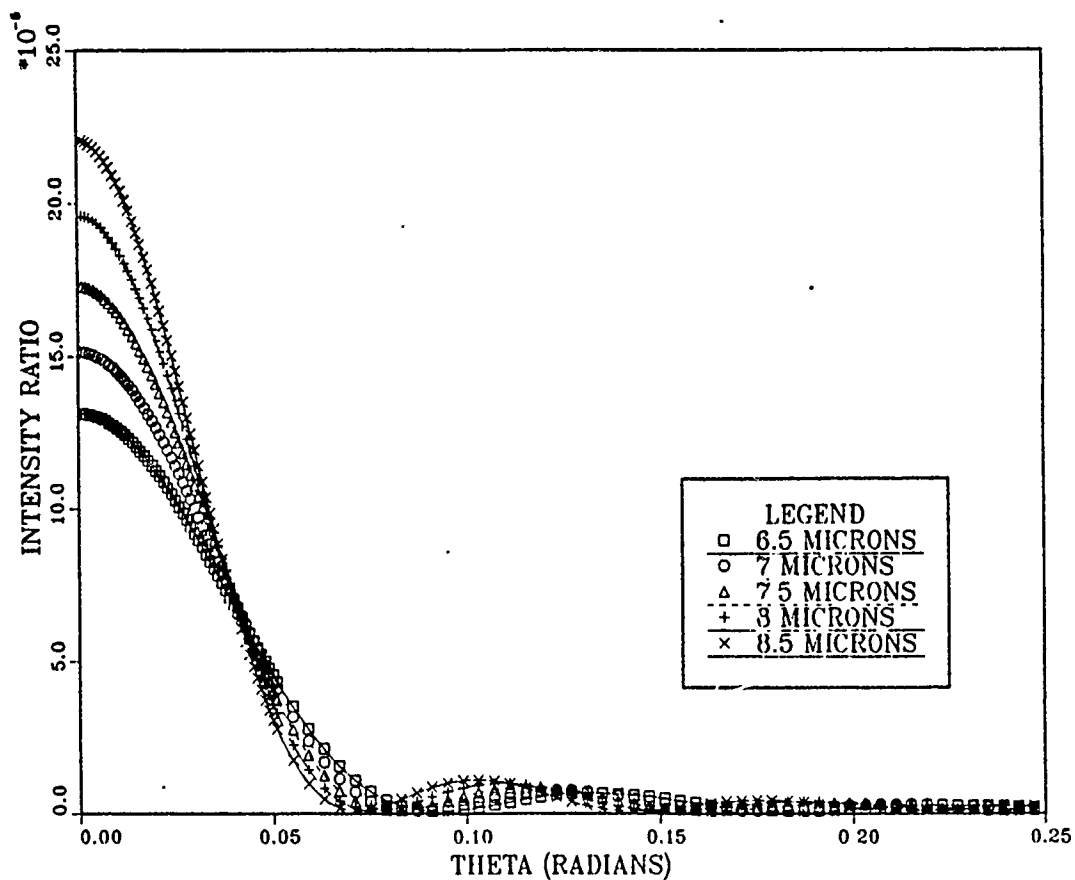
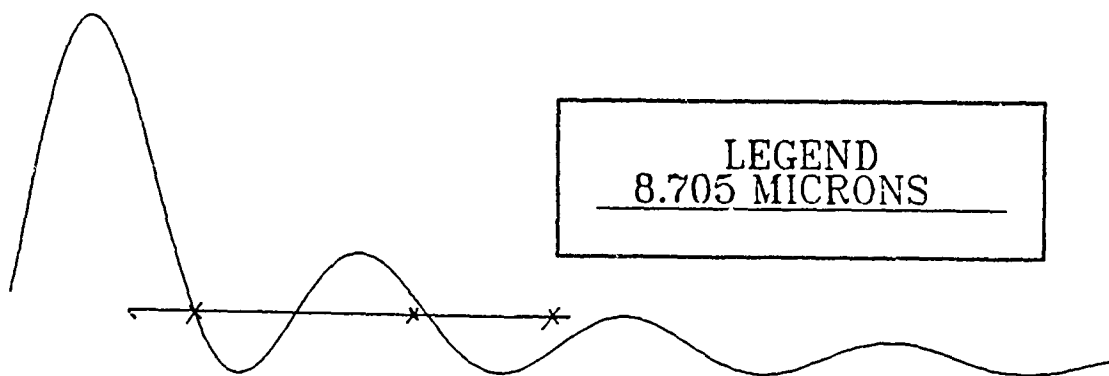
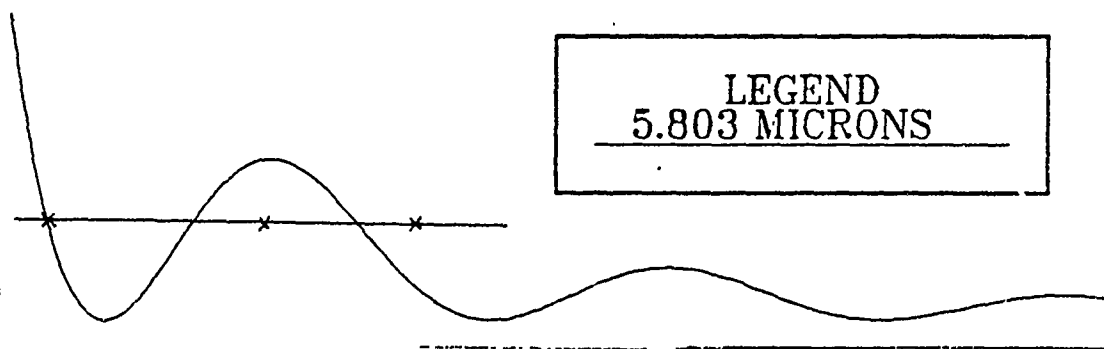
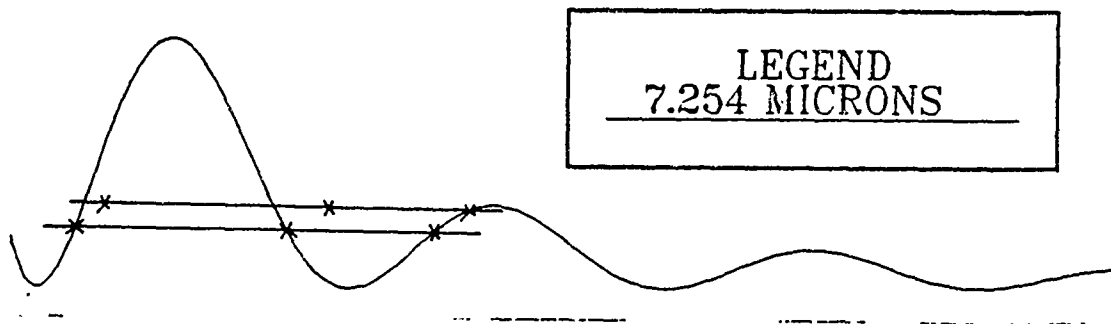


Figure 8. Effect of Diameter on Intensity Profiles (2-D)



Figures 9, 10, 11. Three Points to Define a Curve

2. Maximum derivative

Having heuristically established that three points are required, the next step is to determine the optimum location from which to select the points. For example, if points are selected at the minima (or maxima) a wide variation in theta results from a small change in Intensity Ratio. This variation is defined by the derivative of the Intensity Ratio with respect to Theta, and at the extrema this derivative is very small. It can be shown that the points on the curve where the derivative is a maximum will have the least variation error. Therefore, it is desirable to use the Intensity Ratios corresponding to the maximum derivatives as the optimum intensity ratios for the three points. These Intensity Ratios will be referred to as the Threshold Intensity Ratios.

Figure 12 shows a portion of an Intensity Profile with a derivative curve (absolute value) superimposed. Vertical lines drawn through the derivative curve maxima intersect the Intensity Profile showing the location of the optimum (threshold) intensity points.

INTENSITY PROFILE (PERFECT DATA)

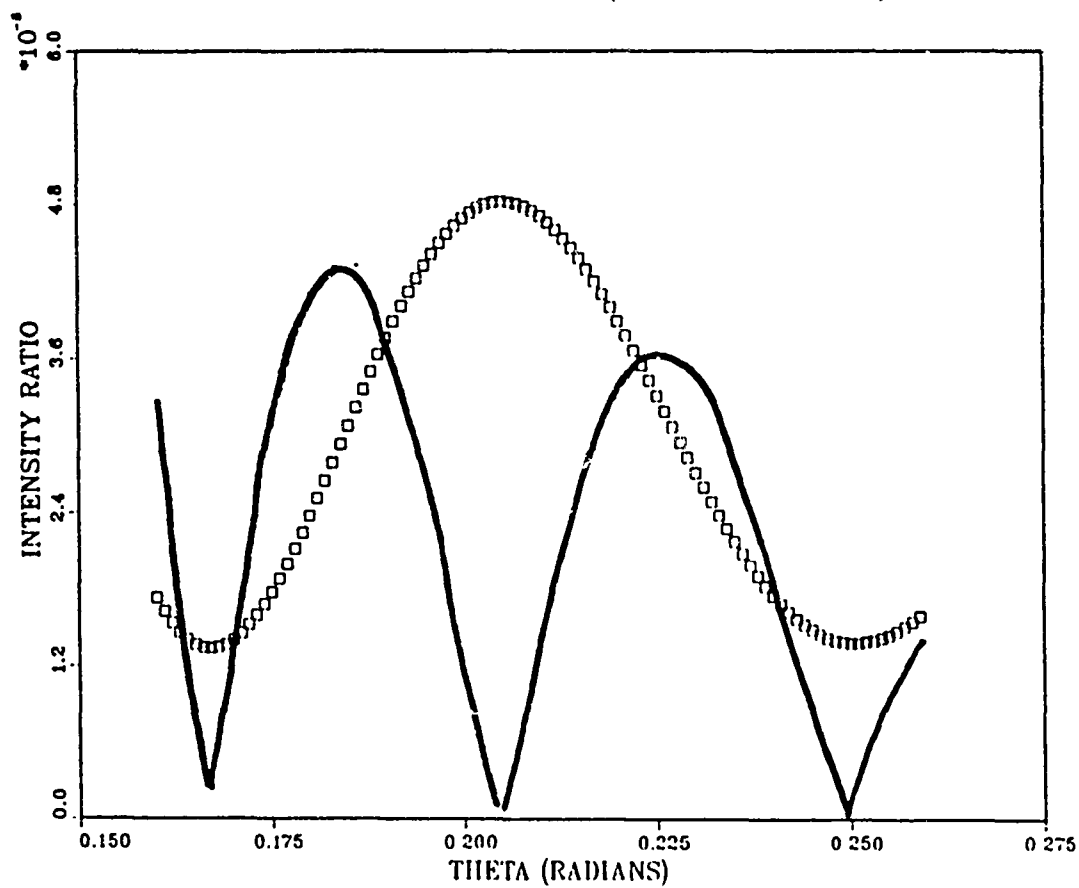


Figure 12. Intensity Profile with Superimposed Derivative Curve

IV. MICRON EYE

The MICRON EYE image sensor is an optically sensitive Random Access Memory (RAM) chip capable of sensing an image and translating it to digital computer compatible signals. The Micron Eye was selected to introduce automation to the existing techniques of fiber diameter measurement by laser diffraction. Automation is expected to increase the speed and accuracy of diameter measurements. This chapter introduces the theory and operation of the Micron Eye.

A. PHYSICAL LAYOUT AND DIMENSIONS

The Micron Eye (IS32 OpticRAM[™]) has two arrays each containing 128 rows x 256 columns of sensors. This application will use only one of the arrays. The size of an array is 4420 μm by 877 μm . (See Figure 13)

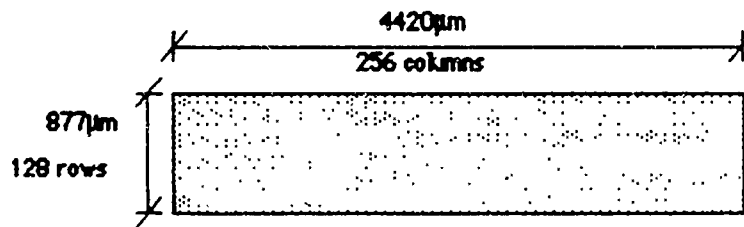


Figure 13. Micron Eye Array

Each sensor is a light sensitive element is called a pixel. The physical organization of the pixels is shown in Figure 14. The 128×256 elements actually map into a 129×514 "cell placement grid". This arrangement leaves "space pixels" in between each pixel in the row direction. The space pixels can be set high, low, or to the level which agrees with the majority of its nearest neighbors.

B. THEORY OF OPERATION

The pixels are capacitors which discharge a preapplied voltage at a rate proportional to both the intensity and duration of the impinging light. The voltage in an exposed capacitor is read and digitally compared to the fixed threshold voltage. If the voltage is below threshold the pixel is read as WHITE. If the voltage is above threshold the pixel is read as BLACK. The digital comparison concept will be an important part of the simulation in the next chapter.

After a pixel is read, the row containing that pixel is refreshed. Refreshing sets all pixels which are below threshold to 0 volts, and all pixels which are above threshold to +5 volts. [Ref. 6]

IS32 OpticRAM™ TOPOLOGICAL INFORMATION

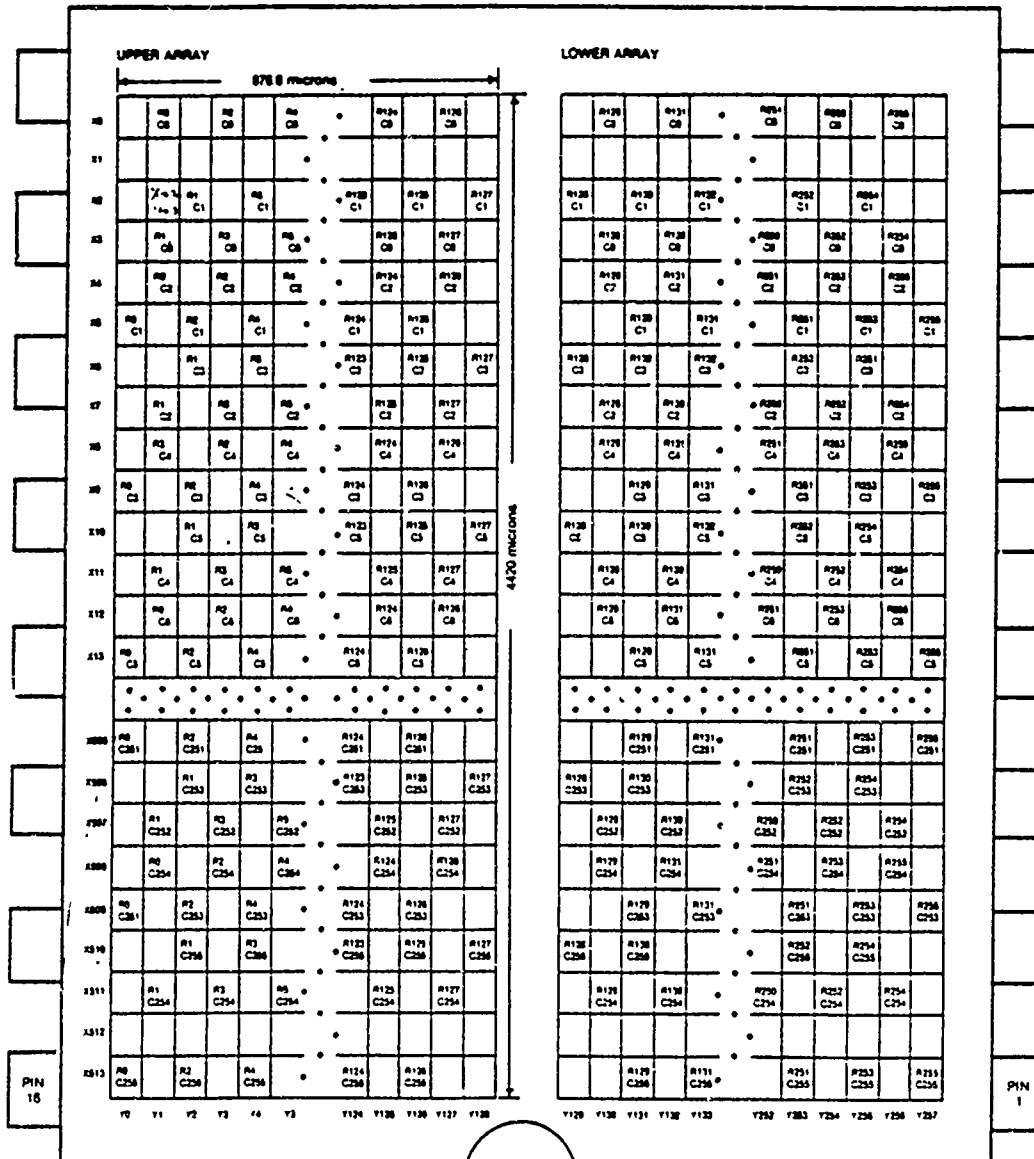


Figure 14. Micron Eye Physical Organization

1. Operation of the Micron Eye

Operation of the Micron Eye is simple. The current research configuration uses an Apple Macintosh (512K) computer. Control software is provided by Micron Technology, Inc. The Micron Eye is connected through either the modem or printer port. (See Figure 15) The computer also acts as the power source for the Micron Eye.

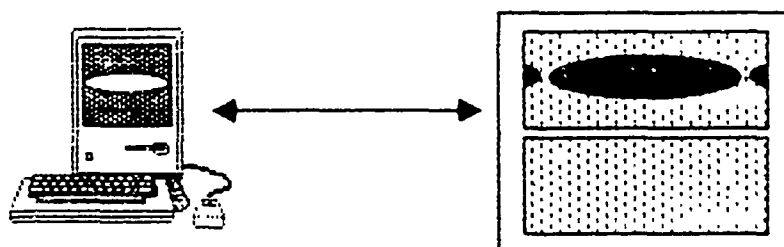


Figure 15. Macintosh and Micron Eye

2. Exposure

An exposure of a portion of the diffraction pattern can be made by varying exposure times. A sample exposure is shown in Figure 16. It is important to visualize that this exposure represents a cross section of the intensity profile curve.

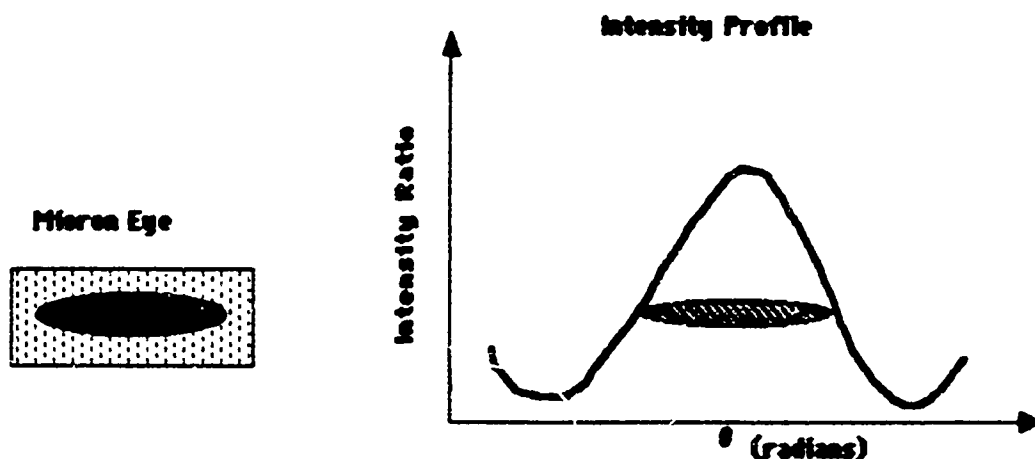


Figure 16. Exposure and Its Relation to Intensity Profile

Longer and shorter exposure times will vary the size of the cross section. Varying exposure time is equivalent to moving up or down the intensity ratio axis of the intensity profile curve.

C. INTENSITY MEASUREMENTS WITH THE MICRON EYE

Bennett [Ref. 4] used the Micron Eye to measure the distance between interference nodes. This approach was compatible with the slit approximation requiring only the theta locations of the interference nodes to give the diameter. In Kerker's equation [Ref. 5:p. 260], one cannot solve explicitly for d . The solution requires knowledge of the Intensity Ratios

and their respective theta locations. For the Micron Eye, Intensity Ratios correspond to the user controlled exposure time.

1. Two Approaches to Intensity Calibration

The Micron Eye must be calibrated to a reference intensity level. One method to accomplish this would require two exposures. One at $I_1 + \Delta$ and another at $I_2 + \Delta$. Delta represents an unknown level above the zero (or absolute) intensity. (See Figure 17) The difference between these two values eliminates delta.

A second method requires a fiber of known diameter. One exposure of this "calibration" fiber will allow determination of the absolute intensity.

INTENSITY PROFILE

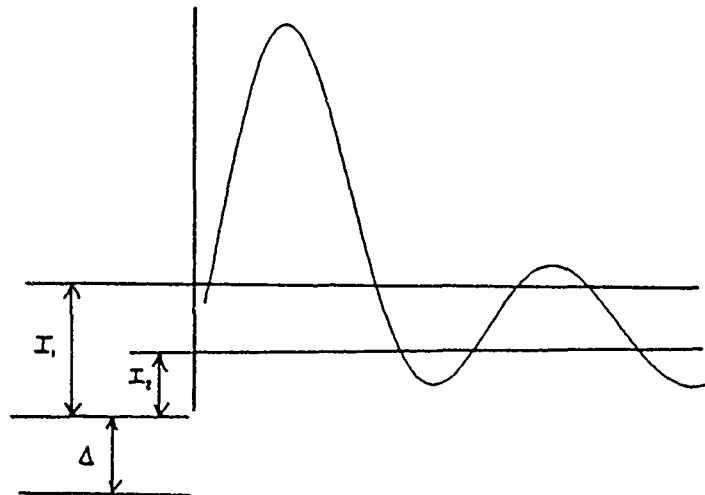


Figure 17. Calibrating the Micron Eye

V. SIMULATION

This chapter introduces the simulation of the Micron Eye / Laser Diffraction diameter measurement system. The simulation answers many questions relating to the real system:

- (1) where should the Micron Eye be placed?
- (2) what exposure is best?
- (3) what accuracy can be expected?
- (4) is the computer code valid?

The simulation combines diffraction pattern analysis with Micron Eye operation. The worth of the results will depend on the accuracy of the simulation.

A. COMPUTER PROGRAMS

Several computer programs have been written to conduct this simulation. These are:

- (1) DATAMAKR
- (2) EXPOSURE
- (3) DIAFIND

Appendix B discusses these programs in detail.

Briefly:

- (1) DATAMAKR is used to produce Intensity Ratio versus Theta data for a given fiber diameter d , and screen to fiber distance L . The user controls the number of points produce and their spacing.
- (2) EXPOSURE reads the Intensity Profile data generated by DATAMAKR and recommends the optimum exposure based on the average of the intensity ratios corresponding to the maximum derivatives. Exposure will also introduce random error into the data, as desired.
- (3) DIAFIND uses the data generated by EXPOSURE to find the diameter of the fiber. The programs begins with a user input guess of the diameter and conducts an iterative search / comparison routine to find the actual diameter of the data.

B. OVERVIEW

The general approach in examining the proposed system will be to consider a typical carbon fiber. This fiber has been assigned the arbitrary diameter of $7.254\mu\text{m}$. Two additional fibers $\pm 20\%$ of the $7.254\mu\text{m}$ fiber are also considered. These fibers define the range of diameters from $5.803\mu\text{m}$ to $8.705\mu\text{m}$. See Figures 18, 19, and 20 for Intensity Profiles curves for these diameters.

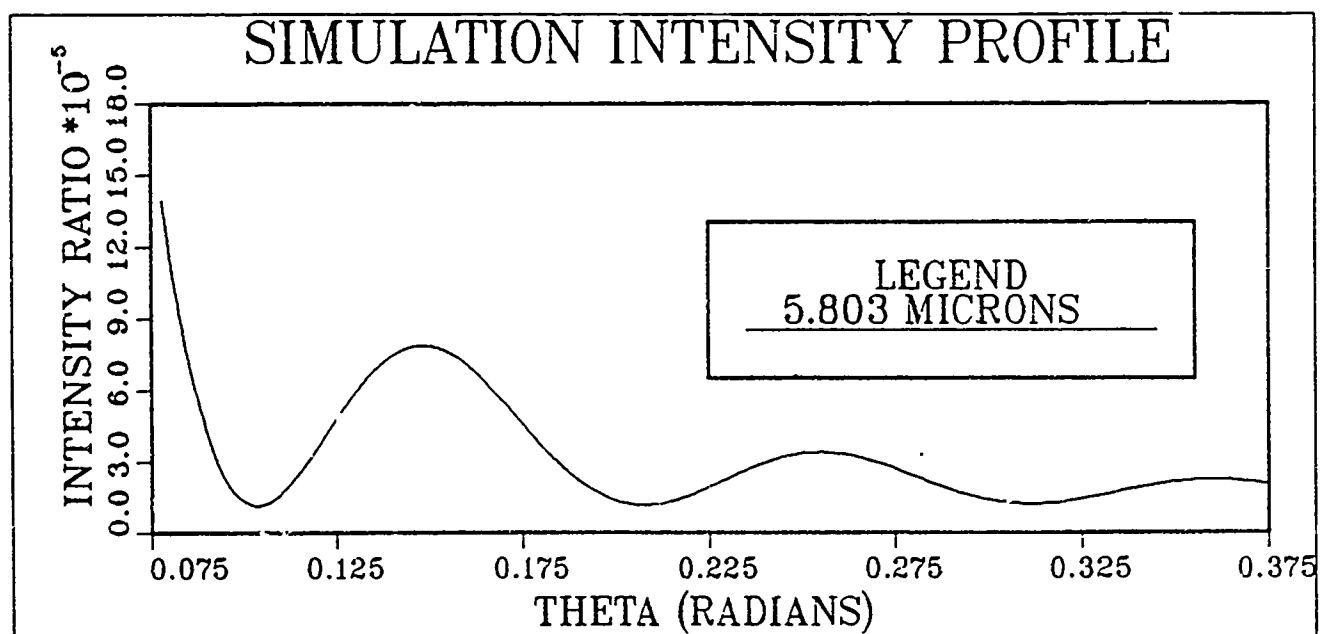


Figure 18. Simulation Intensity Profile (5.803 μ m)

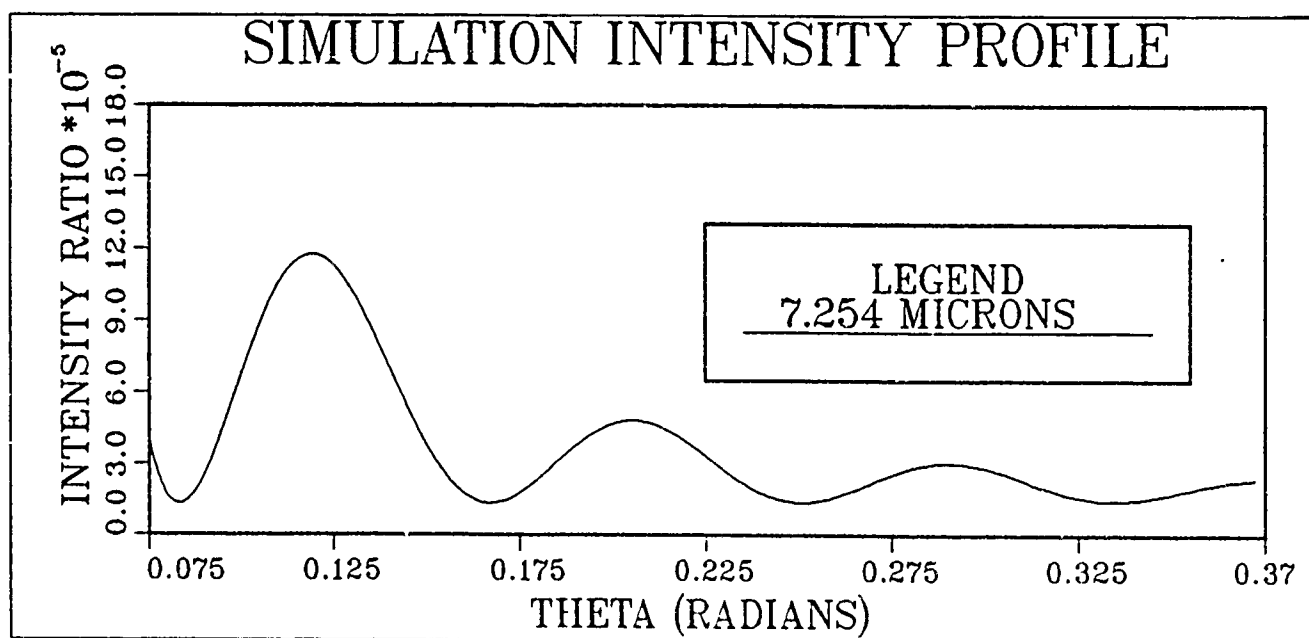


Figure 19. Simulation Intensity Profile (7.254 μ m)

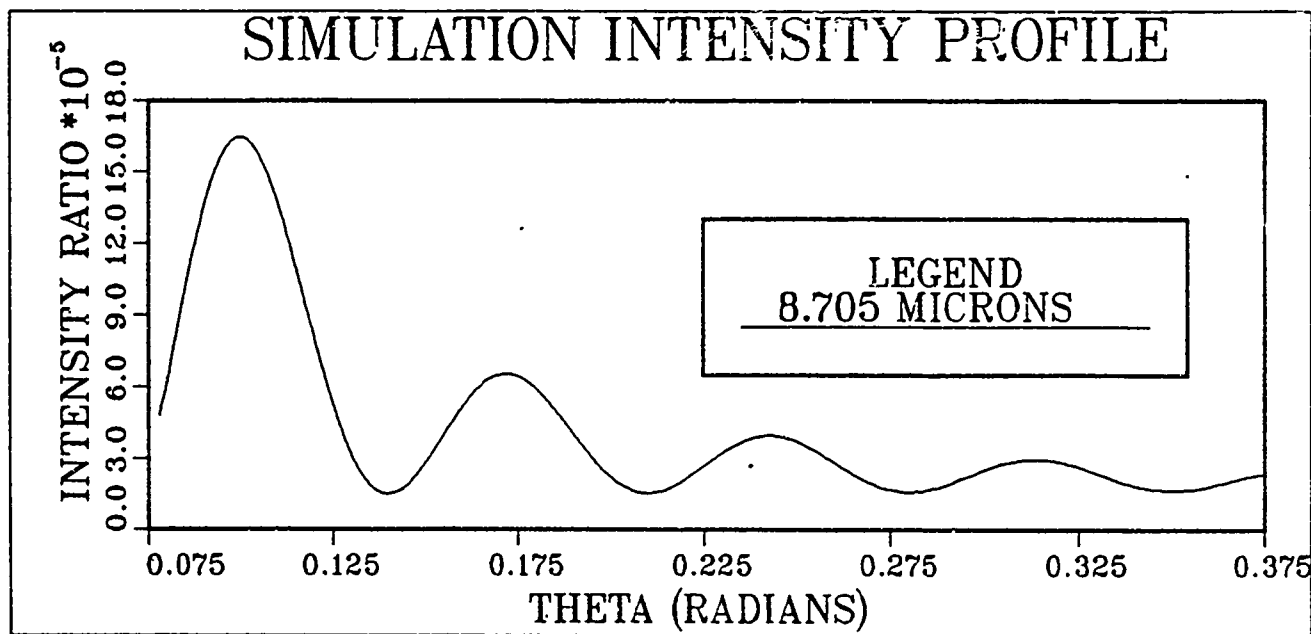


Figure 20. Simulation Intensity Profile (8.705 μ m)

C. POSITIONING OF THE MICRON EYE

In order to measure the diameter of the typical fiber, a method of positioning the Micron Eye must be defined. Further, from this same position, it is desired to also measure the $\pm 20\%$ fibers. This requires that one position of the Eye permit fiber diameter measurements over the specified range of fiber diameters.

Such a position is defined such that three data points will be obtained for any fiber in the diameter range, as in Figure 21. First, a simpler case will be discussed to introduce positioning for a given diameter fiber.

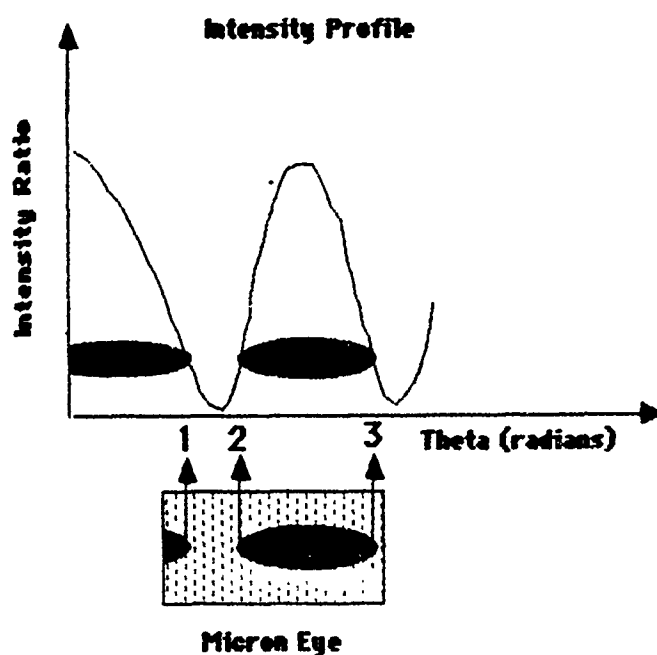


Figure 21. Exposure for Three Data Points

1. Positioning for a Single Fiber

Suppose an exposure of the first through the second interference nodes (2nd maximum) was desired for the 7.254 μ m fiber. Figure 22 shows the relationship between the fiber and the Micron Eye:

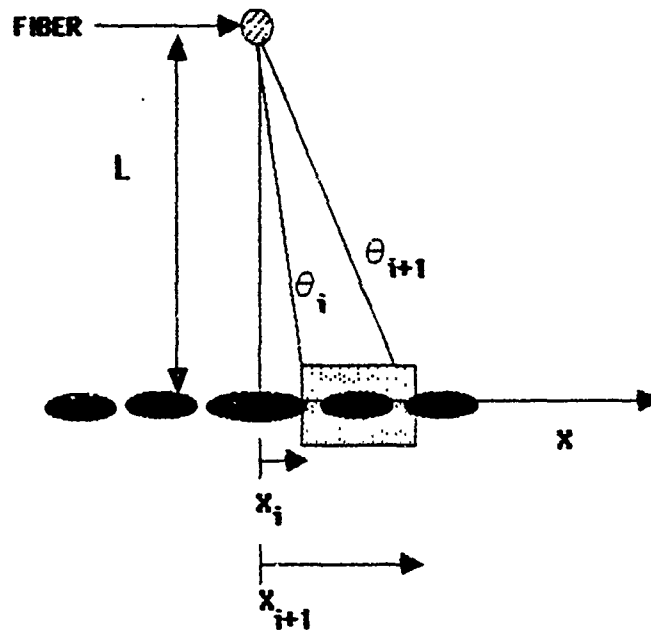


Figure 22. Micron Eye Placement in Diffraction Pattern

$$\theta_i = \tan^{-1} [x_i / L] \quad (3)$$

$$\theta_{i+1} = \tan^{-1} [x_{i+1} / L] \quad (4)$$

$$\text{or } \tan \theta_{i+1} - \tan \theta_i = 1/L (x_{i+1} - x_i) = \Delta x/L \quad (5)$$

take $\Delta x = 4.4 \text{ mm}$ (width of Micron Eye array)

With Δx fixed, one can adjust L so that any desired $\theta_{i+1} - \theta_i$ will fit on the Micron Eye's array. Recall that $\theta_{\min} = \sin [m\lambda / d]$ equation (2), which will give the theta locations of the first and second interference nodes.

$$\theta_{\min} = \sin (m\lambda/d) \quad \text{where } m = \text{node} *$$

$\lambda = \text{laser wavelength (632.8nm)}$

$d = \text{fiber diameter}$

$$\text{for } 7.254\mu\text{m: } \theta_i = .08712 \text{ radians}$$

$$\theta_{i+1} = .17459 \text{ radians} \quad (\text{for } i = 1)$$

with θ_i and θ_{i+1} fixed, L is defined from equation (5):

$$L = \Delta x / [\tan \theta_{i+1} - \tan \theta_i] = 49 \text{ mm}$$

L is the distance of the Micron Eye from the fiber in the longitudinal direction. Referring back to equation (3), the lateral placement of the Eye is given (see Figure 23):

$$x_{\text{inner}} = L \tan(\theta) = 4.27 \text{ mm}$$

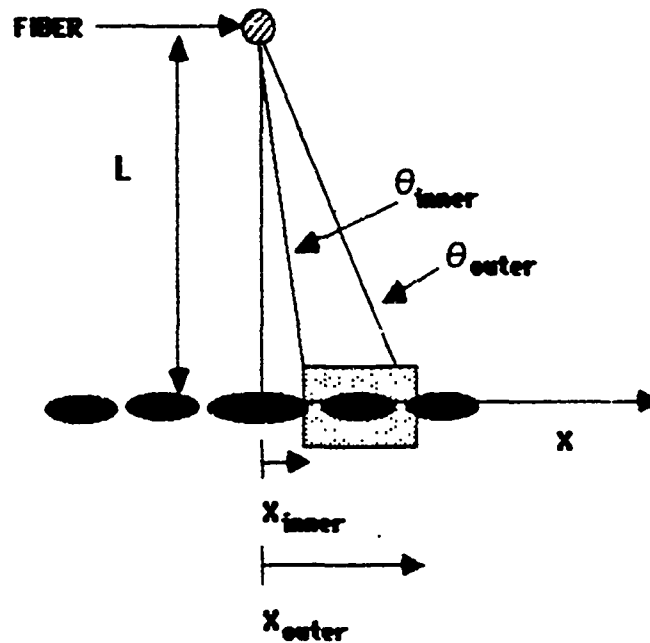


Figure 23. Micron Eye Position

Thus, equations (3) through (5) give the Micron Eye position for any desired d , θ_{t+1} , θ_t , L and m .

This position is not yet optimum for single diameter case. This analysis has captured only two interference nodes and the intervening maximum. Any exposure will yield information somewhere between the two extremes shown in Figure 24. The Micron Eye images correspond to the shaded areas of the intensity profile curve on the right side of Figure 24.

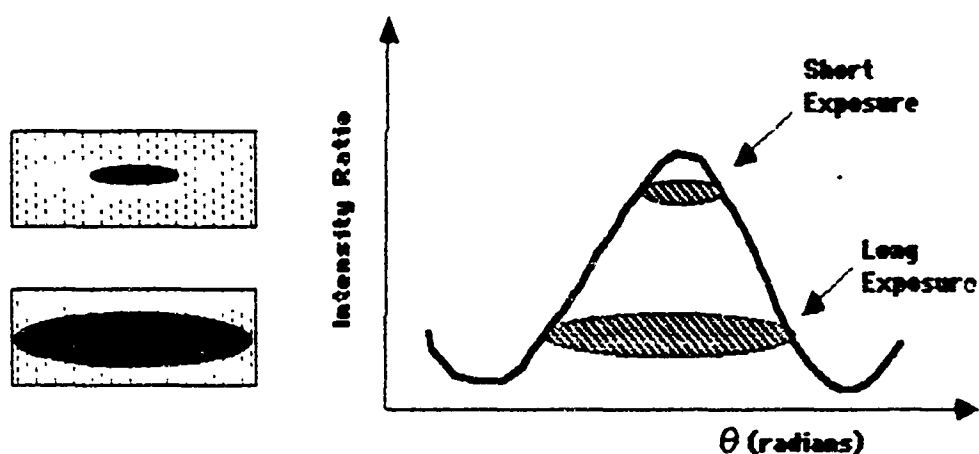


Figure 24. Short and Long Exposures

One method of finding the points would be to search the Micron Eye array data for a major axis. The endpoints of this major axis are the points required for the analysis. (See Figure 25)

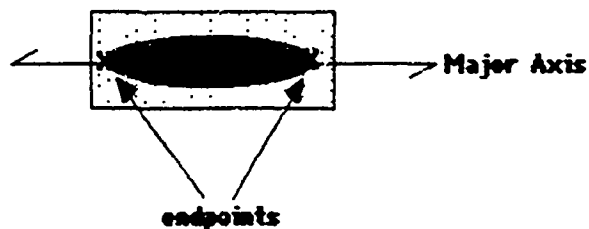


Figure 25. Endpoints of Major Axis

Recall from diffraction analysis (Chapter 3) that three points are required to define the intensity profile curve. Therefore, more of the diffraction pattern must be seen by the Micron Eye. A reduction in L will yield the third point. (See Figure 26) L should not be reduced any more than is necessary, since fewer pixels are being used to describe the data, degrading the resolution of the Micron Eye.

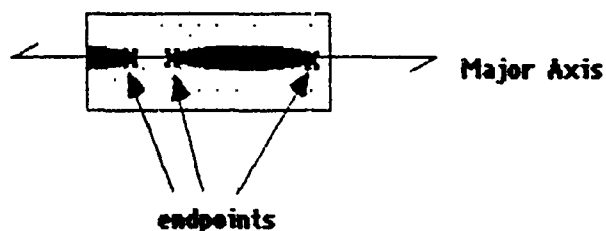


Figure 26. Three Points on Major Axis

2. Positioning the Micron Eye for a Range of Diameters

Consider the positioning of the Micron Eye so that three data points can be collected for a range of diameters. A "window" for the array must be defined which will ensure three points of data for any diameter in the specified range.

Examine the Relative Intensity Profile plot in Figure 27. θ begins at .075 radians which excludes the the central maximum. The central maximum is so intense, the Micron Eye's fastest exposure cannot prevent overexposure. Therefore, the central maximum is not considered as a location for the window.

The window should also be located in a region where the maximum intensity corresponding the the largest diameter fiber is close to the maximum intensity of the smallest diameter fiber. This ensures the Threshold Intensity Ratio will be more representative for all diameter in the range. This condition occurs at the higher order nodes (2 or greater), as illustrated in Figure 28. The plot of intensity ratio derivatives also shows this condition in Figure 29.

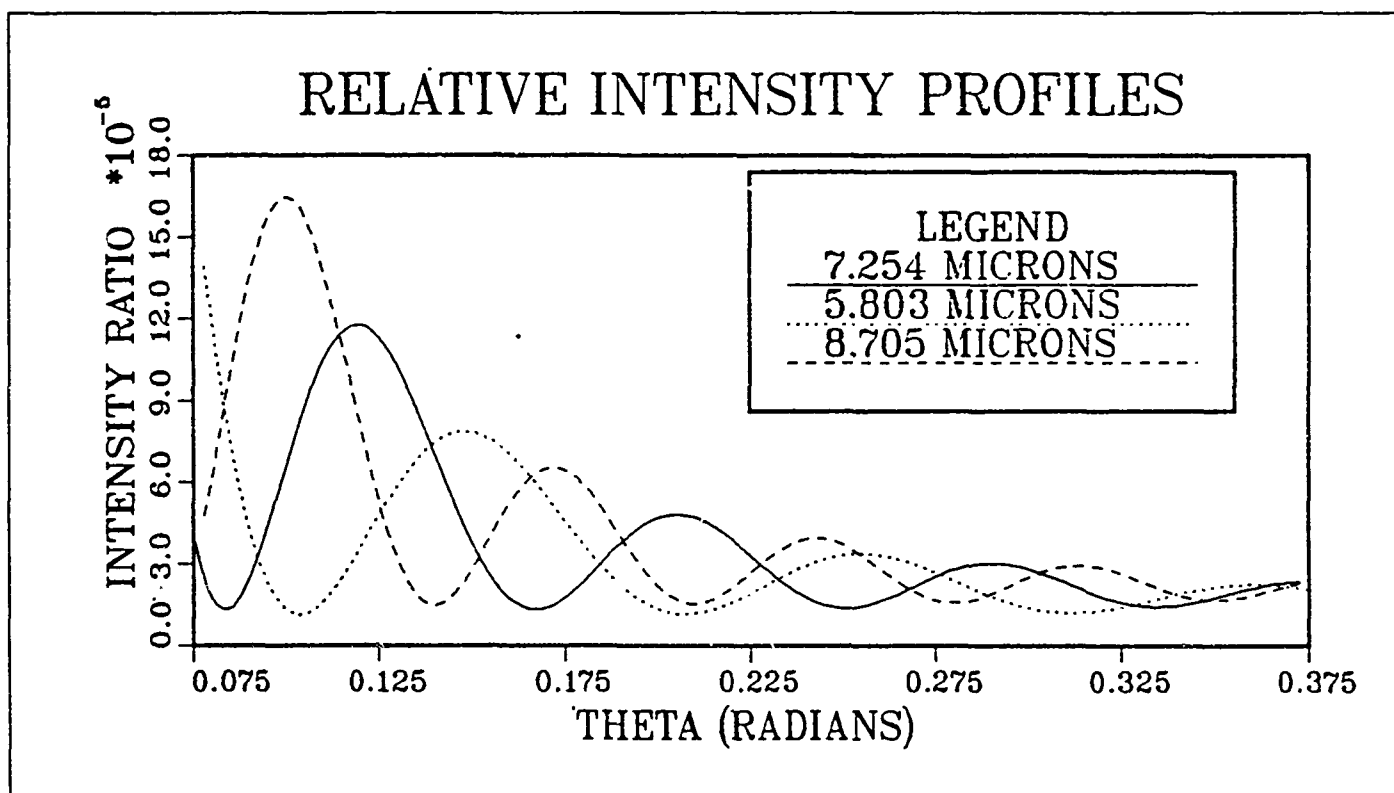


Figure 27. Relative Intensity Profiles

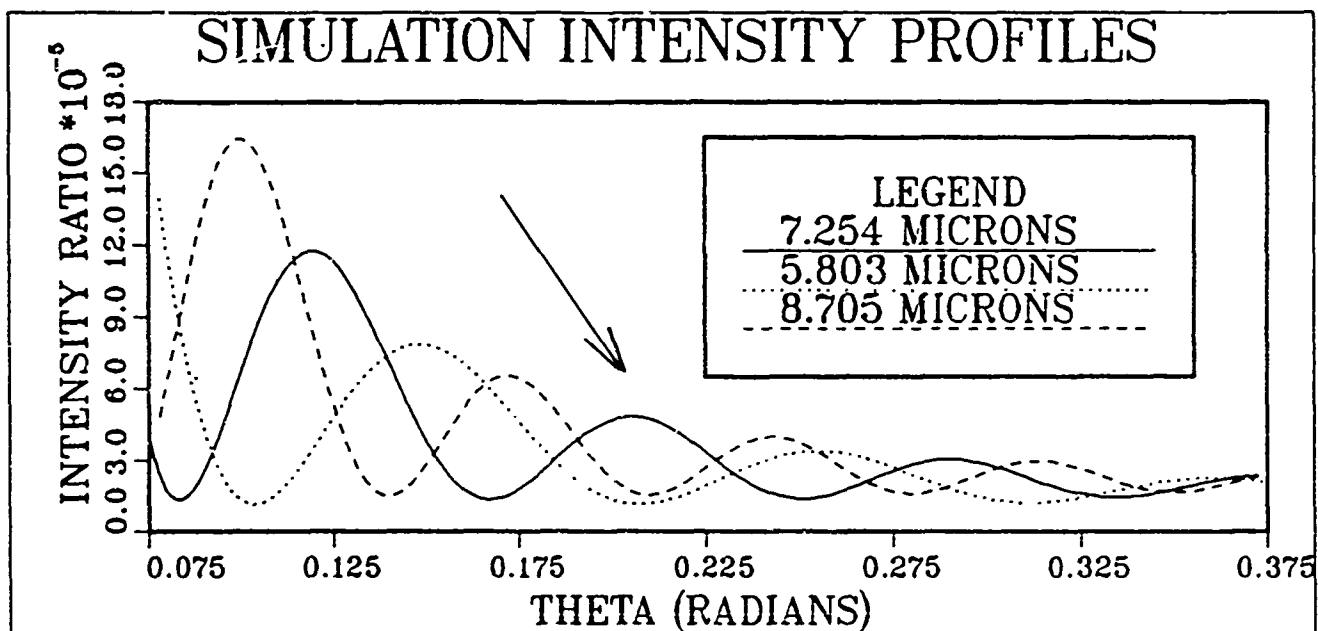


Figure 28. Region of Similar Maximum Intensities

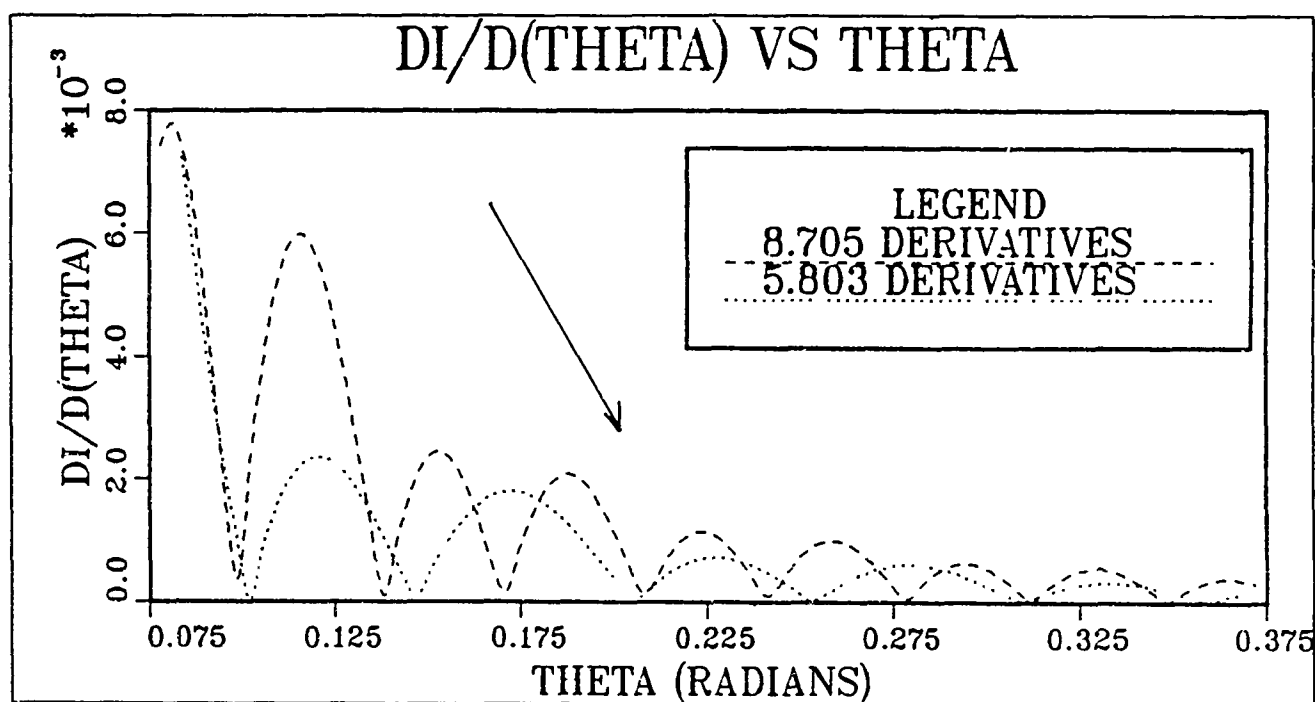


Figure 29. Region of Similar Intensity Ratio Derivatives

To obtain three points, at about 1.5 maxima are required. Since the distance between nodes is the greatest for the smallest diameter, find the θ locations for the smallest diameter which gives 1.5 maxima.

for $5.803\mu\text{m}$:

$$\theta_{\text{min}2} = \sin(21/5.803\mu\text{m}) = .216 \text{ rads}$$

$$\theta_{\text{min}3} = \sin(31/5.803\mu\text{m}) = .321 \text{ rads}$$

Half of this range is about .050 radians and 1.5 maxima can be approximated by .165 -----> .321 radians. Admittedly, this is not a sophisticated method. The method is somewhat liberal and it was later discovered that a range of .165 to .300 radians was better than the larger range. This is because the minima are not of interest so the right hand minimum at .321 radians was discarded, and the range reduced to .300 radians. Only the part of the curve where the slope is a maximum needs to be "seen" by the array.

A quick check can be made to insure that the curve representing the maximum diameter in the range fits inside the window.

for $8.705\mu\text{m}$:

$$\theta_{\text{min}2} = \sin(21 / 8.705) = .150 \text{ rads}$$

$$\theta_{\text{min}3} = \sin(31 / 8.705) = .216 \text{ rads}$$

$$\theta_{\text{min}4} = \sin(41 / 8.705) = .286 \text{ rads}$$

The next step is to determine the distance L at which the Micron Eye will cover the θ range of .165 ---> .300 radians. Equation (5) defines the longitudinal position and equation (3) defines the corresponding lateral position:

$$L = \Delta x / [\tan(\theta_{i+1}) - \tan(\theta_i)] = 30 \text{ mm}$$

$$x_i = L \tan(\theta_i) \approx 5 \text{ mm} \quad (\text{inboard position of array})$$

VI. SIMULATION: THE PERFECT AND IMPERFECT DATA SETS

Now that a window has been defined (θ range) for the diameter range, it is necessary to construct perfect data for the simulation diameters: d_1 , d_2 , and d_3 . DATAMAKR generates this data for a given d and L , over the specified range of θ . Additionally, the number of points over the specified range must be chosen. The number of points defines the θ interval and corresponds to the physical spacing of the pixels in the Micron Eye array which is on the order of $10\mu\text{m}$. To match this spacing, 400 points were generated over the interval .165 to .300 radians.

A. DIGITIZATION OF DATA

The EXPOSURE program is used to digitize the perfect data. Digitizing the data is the simulative analog of the Micron Eye threshold voltage comparison. In the simulation, any intensity ratios above a certain ratio (call it the *threshold ratio*) are assigned a value of 1 and any intensity ratio below the threshold ratio are assigned a value of 0.

1. Determining the Threshold Intensity Ratio

Before EXPOSURE can digitize the perfect data, the threshold ratio must be determined. EXPOSURE calls the subroutine DERIV which calculates the derivatives of the intensity profile data at each theta location.

DERIV proceeds to search for all the local maximum derivatives. The average of the maximum derivatives is returned to the EXPOSURE program and is used as the threshold intensity.

After the data is digitized with respect to the threshold intensity, the digital data is searched to find the theta locations where the intensity changes from 0 \rightarrow 1 or 1 \rightarrow 0. The values for theta at these locations are averaged and this average is taken to be the theta location where the threshold intensity is located. The averaging of theta is based on the fact the Intensity Profile curve is approximately linear in the region of the Threshold Intensity Ratio. Figure 30 shows the general location of the Threshold Intensity Ratio.

In the simulation, EXPOSURE finds three average theta locations corresponding to the threshold intensity ratio. These data are stored in a data file which is subsequently input to the program DIAFIND. DIAFIND prompts the user to input an initial guess of the diameter and proceeds to find the diameter associated with the EXPOSURE data.

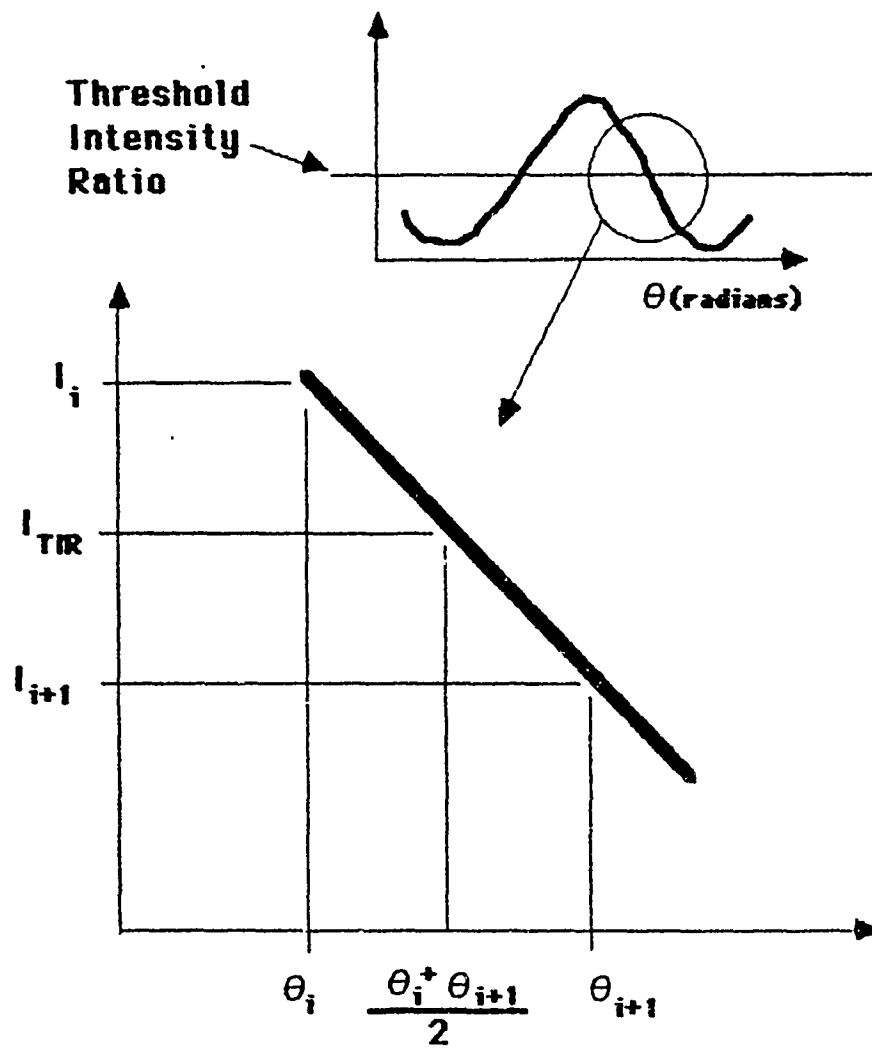


Figure 30. Averaging of Theta

3. INTRODUCTION OF ERROR INTO THE PERFECT DATA

EXPOSURE prompts the user for an error input. If error is desired, EXPOSURE calls the subroutine RANDOM. RANDOM introduces error based on the maximum intensity ratio in the perfect data:

$$I_{err} = I_0 + [I_{max} * ERROR * RND]$$

where ERROR is the error to be introduced and RND is a random number between ± 1 generated by the NONIMSL subroutine RANDU. RANDOM returns the now "imperfect" intensity ratios to the EXPOSURE program.

C. DIGITIZATION PROBLEMS WITH THE IMPERFECT DATA

Digitizing the imperfect data results in local regions where the intensity oscillates between 0 and 1, as shown in Table 1. The introduction of random error changes the smooth curve to erratic points. Locally, variations above and below the threshold intensity ratio cause a series of 0-->1 and 1-->0 oscillations. (See Figure 31) Ideally, only one local theta location is to be associated with the threshold intensity ratio.

There are two approaches to this problem. First, the average of the local theta locations can be calculated. This method results in three theta locations for input into the DIAFIND program (the same as perfect data).

TABLE 1. DIGITIZATION ERROR

THETA LOCATION	INTENSITY RATIO
0.2321624000E 00	0.3544308000E-04 1
0.2324997000E 00	0.3196243000E-04 1
0.2328373000E 00	0.3160309000E-04 1
0.2331748000E 00	0.3246925000E-04 1
0.2335124000E 00	0.3372986000E-04 1
0.2338498000E 00	0.3785736000E-04 0
0.2341873000E 00	0.3090432000E-04 1
0.2345249000E 00	0.3342219000E-04 1
0.2348623000E 00	0.3387519000E-04 1
0.2351998000E 00	0.3205373000E-04 1
0.2355374000E 00	0.3516222000E-04 1
0.2358747000E 00	0.3860490000E-04 0
0.2362123000E 00	0.3421140000E-04 1
0.2365499000E 00	0.3468163000E-04 1
0.2368872000E 00	0.3580747000E-04 1
0.2372248000E 00	0.3904779000E-04 0
0.2375622000E 00	0.3578593000E-04 1
0.2378997000E 00	0.3912353000E-04 0
0.2382373000E 00	0.3599435000E-04 1
0.2385748000E 00	0.3474336000E-04 1
0.2389124000E 00	0.3538676000E-04 1
0.2392498000E 00	0.3470230000E-04 1
0.2395873000E 00	0.3952176000E-04 0
0.2399249000E 00	0.392357000E-04 0
0.2402623000E 00	0.3944175000E-04 0
0.2405998000E 00	0.3966210000E-04 0
0.2409374000E 00	0.4409726000E-04 0
0.2412747000E 00	0.4269459000E-04 0
0.2416123000E 00	0.4371968000E-04 0
0.2419497000E 00	0.3904802000E-04 0

ERROR SIMULATION

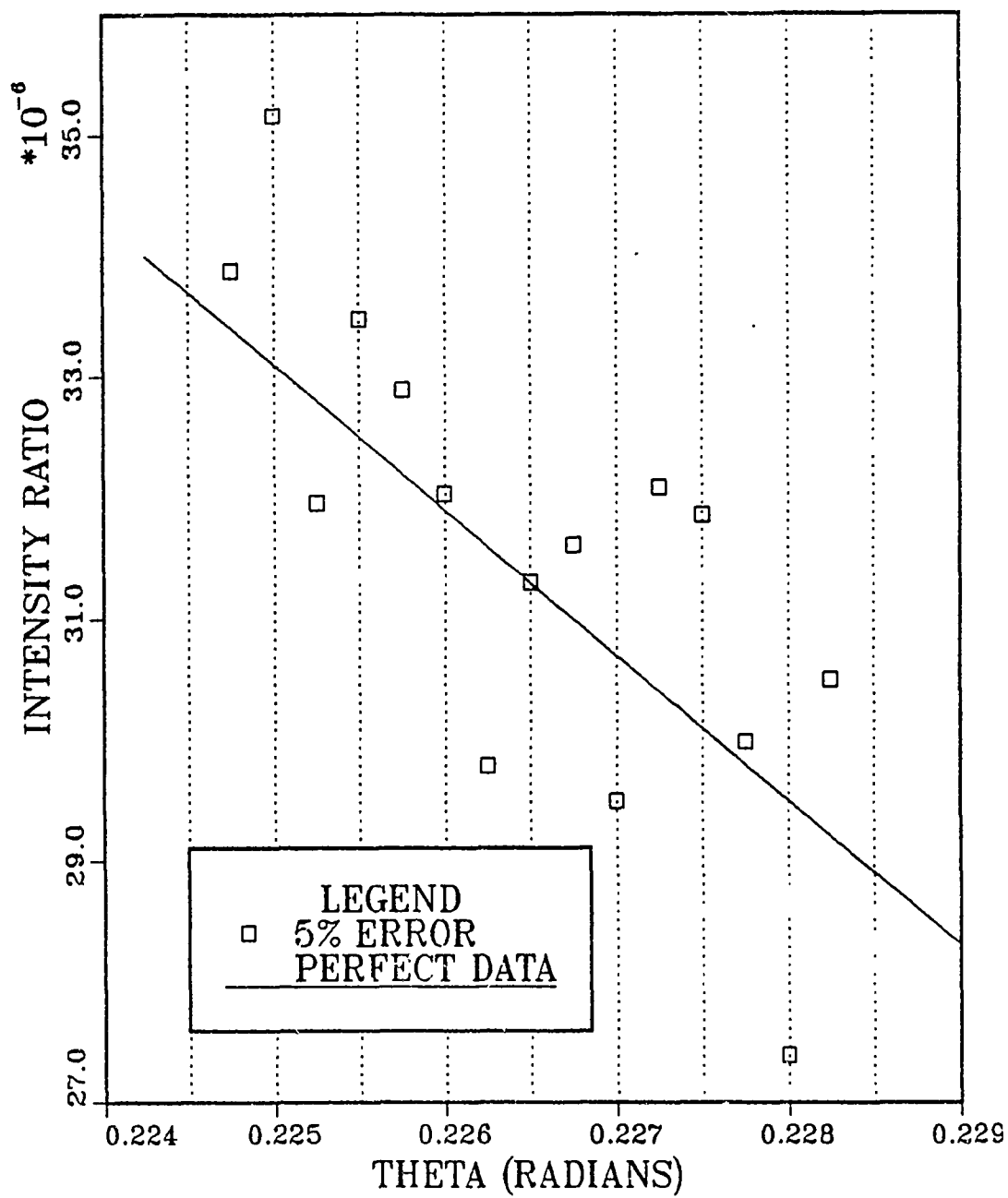


Figure 31. Intensity Variation at 5% Error

The second method is to accept the theta locations as they are and enter them into the DIAFIND program. The latter method will pass a variable number of data points to DIAFIND.

Both approaches were tested (at 5% error for 7.254 μm) and the same diameter was recovered by DIAFIND in each case. The only difference between the two methods is that the averaging method runs one second faster (out of 22 seconds on the IBM 360) than the other method.

The averaging method was adopted for this simulation for two reasons:

- (1) The data input to DIAFIND will always be a constant number of points so that DIAFIND can be easily adapted to run actual Micron Eye data without simulation related logic buried in the code.
- (2) The averaging method returns the same diameter as the other method.

D. CHOOSING THE CORRECT EXPOSURE (TUNING)

The optimum exposure for this simulation was calculated by the program EXPOSURE. It was an average value of the intensity ratios associated with the maximum derivatives locations for the 7.254 μm fiber data. This same exposure was used throughout the simulation for all the fibers.

Using the same exposure introduces realism into the simulation since one cannot tune the exposure for every fiber that is to be measured. Because the Micron Eye window is located at least two nodes out from the

central maximum the exposure is closer to optimum for all diameters over the range. (In contrast to a window location closer to the central maximum.)

The process EXPOSURE uses to determine the threshold intensity ratio can be called "tuning". The Micron Eye analog of tuning would consist of three steps:

- (1) Determine the approximate diameter for the fiber to be measured using an optical shearing eyepiece.
- (2) Determine the Micron Eye location parameters L and x by the methods in Chapter 5.
- (3) Vary exposure to obtain a defined relationship between the three points on the Micron Eye photograph.

As an example, return to the case where $L = 30$ mm and $x_{\text{inner}} = 5$ mm.

(x_{inner} is the inboard x location of the Micron Eye array.) Figure 32 shows the "tuned" relationship between three points on the Micron Eye array. This relationship can be expressed as a ratio of $a : b : c$. The theta locations at the inboard and outboard edges of the Micron Eye are known.

e.g., $\theta_{\text{inner}} = .165$ radians and $\theta_{\text{outer}} = .300$ radians.

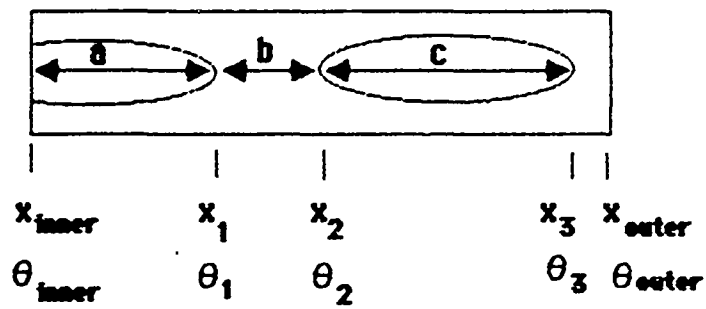


Figure 32. Three Point Spacing Ratio

This means that $\theta_{inner} < \theta_1 < \theta_2 < \theta_3 < \theta_{outer}$.

To find θ_1 , θ_2 , and θ_3 , run EXPOSURE for the diameter being tuned. EXPOSURE outputs the theta values for the optimum exposure. (See Figure 33)

The theta values are related to x locations by:

$$x_1 = L \tan(\theta_1)$$

$$x_2 = L \tan(\theta_2)$$

$$x_3 = L \tan(\theta_3)$$

where

$$a = x_1 - x_{inner}$$

$$b = x_2 - x_1$$

$$c = x_3 - x_2$$

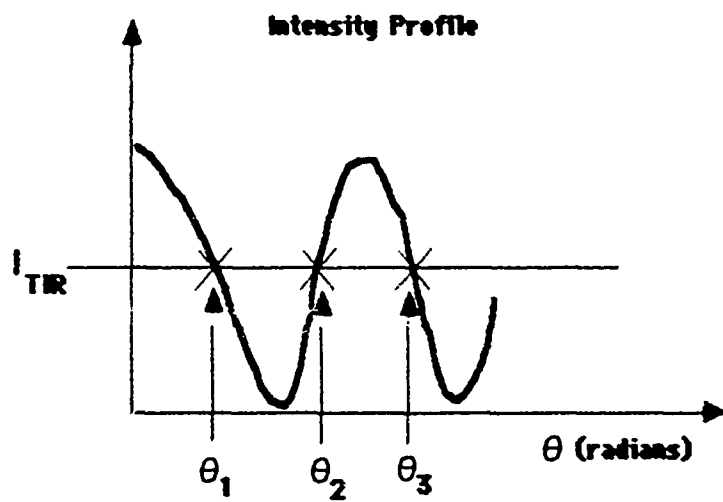


Figure 33. Finding the Theta Locations

VII. DISCUSSION OF RESULTS

The simulation was conducted for three diameters:

$$d_1 = 5.803 \mu\text{m}$$

$$d_2 = 7.254 \mu\text{m}$$

$$d_3 = 8.705 \mu\text{m} \quad (\text{where } d_1 \text{ and } d_3 \text{ are } \pm 20\% d_2)$$

For each d_i , three levels of error were introduced: 1%, 2% and 5%.

Figure 34 shows the three intensity profile curves for the d_i .

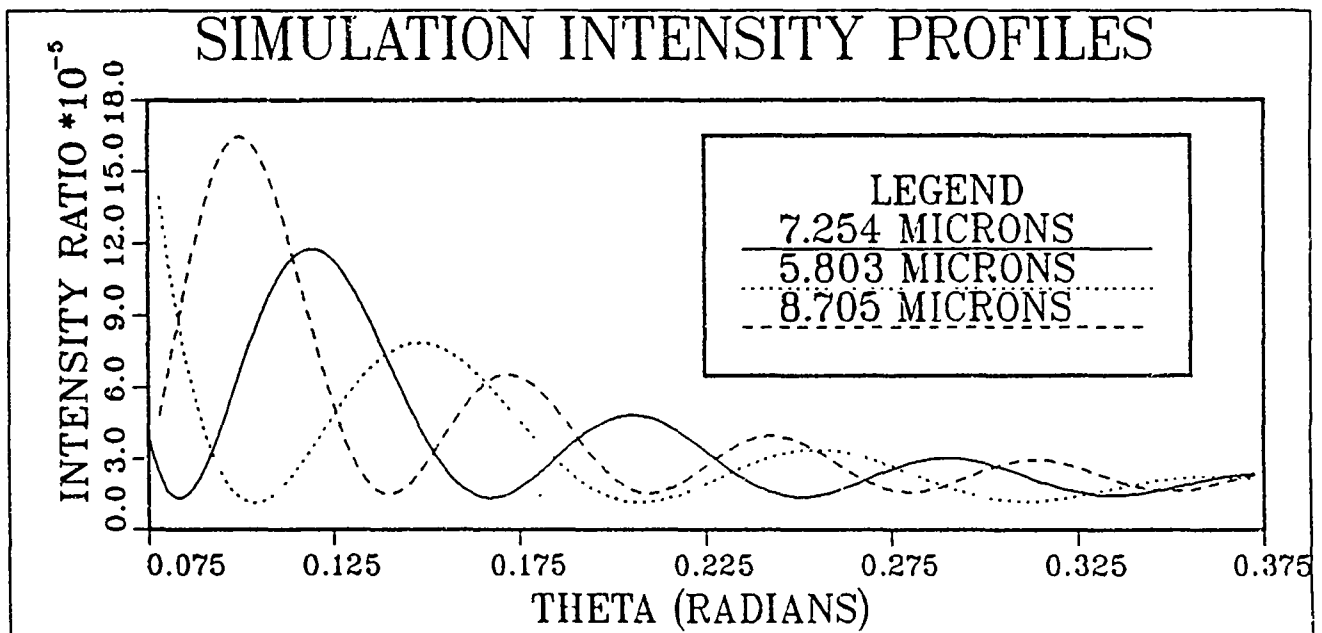


Figure 34. Simulation Intensity Profiles

The simulated Micron Eye window was determined as previously described at $L = 30\text{mm}$ and $x_{\text{inner}} = 5\text{mm}$. The exposure was tuned with respect to the $7.254\mu\text{m}$ perfect data. EXPOSURE recommended the Threshold Intensity Ratio of .0000370. This Threshold Intensity Ratio remained constant throughout the simulation, for all diameters.

Before the simulation, all diameters were tested with no error using the $7.254\mu\text{m}$ Threshold Intensity Ratio. DIAFIND recovered d_1 , d_2 and d_3 exactly (i.e., to the three digits accuracy of the original diameters).

The simulation originally began by collecting thirty data points for each diameter/error combination. Twenty additional points were collected (50 total) to produce meaningful histograms.

Figures 35 through 43 are histograms depicting the results of the simulation. In general, the expectation was to see a decrease in resolution as more error was introduced. It was also anticipated the resolution would be best for the $7.254\mu\text{m}$ case (for all values of error) since the exposure was "tuned" for this diameter. Finally, it was hoped the method would be more accurate than existing laser diffraction measurement methods ($\approx 0.5\%$).

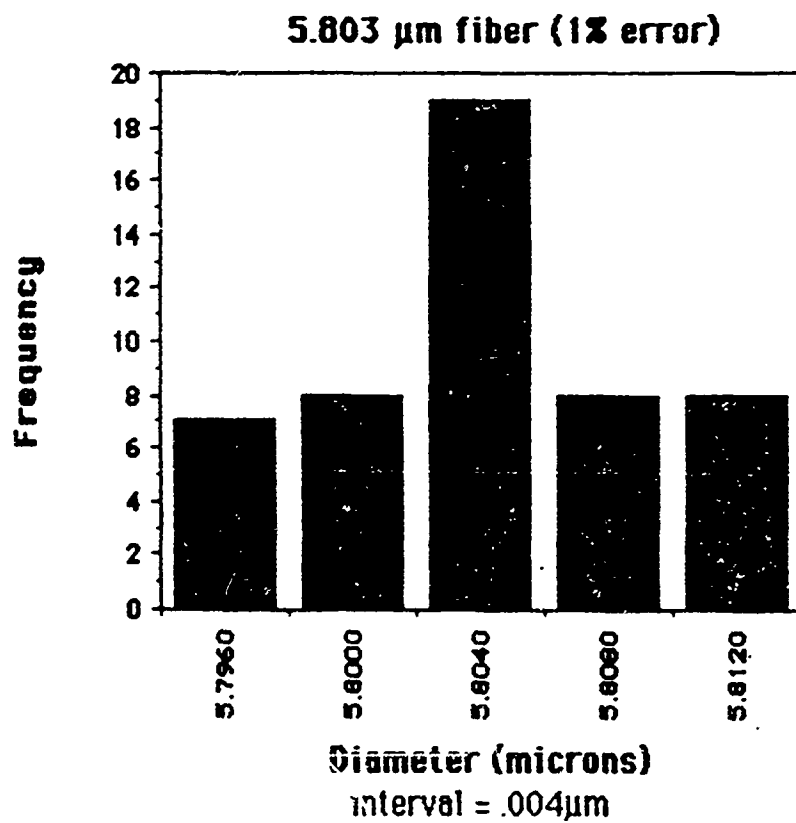


Figure 35. 5.803 μm Fiber (1% error)

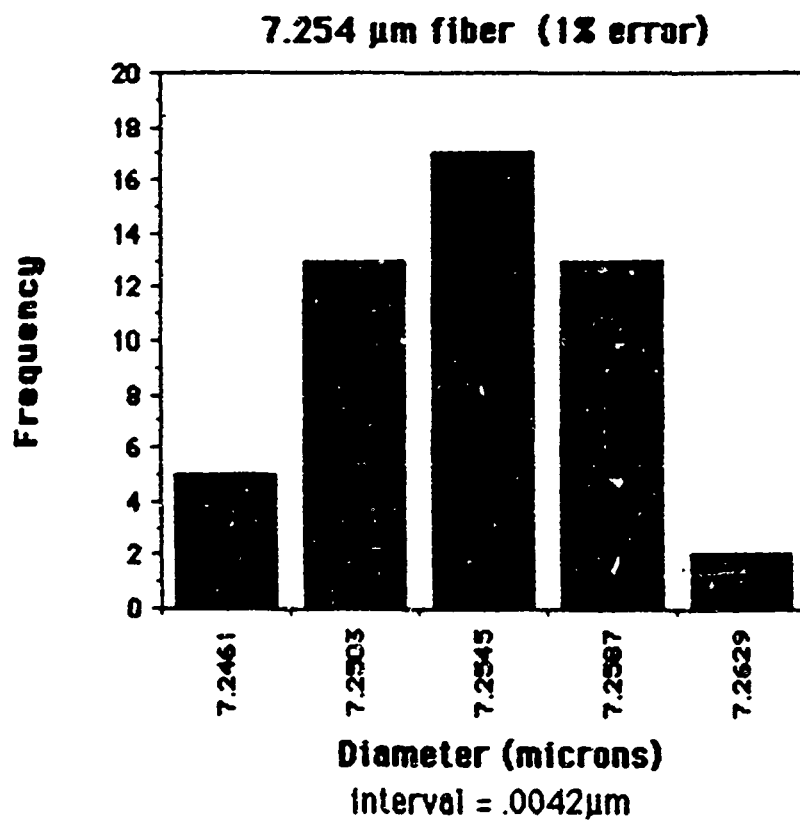


Figure 36. 7.254 μm Fiber (1% error)

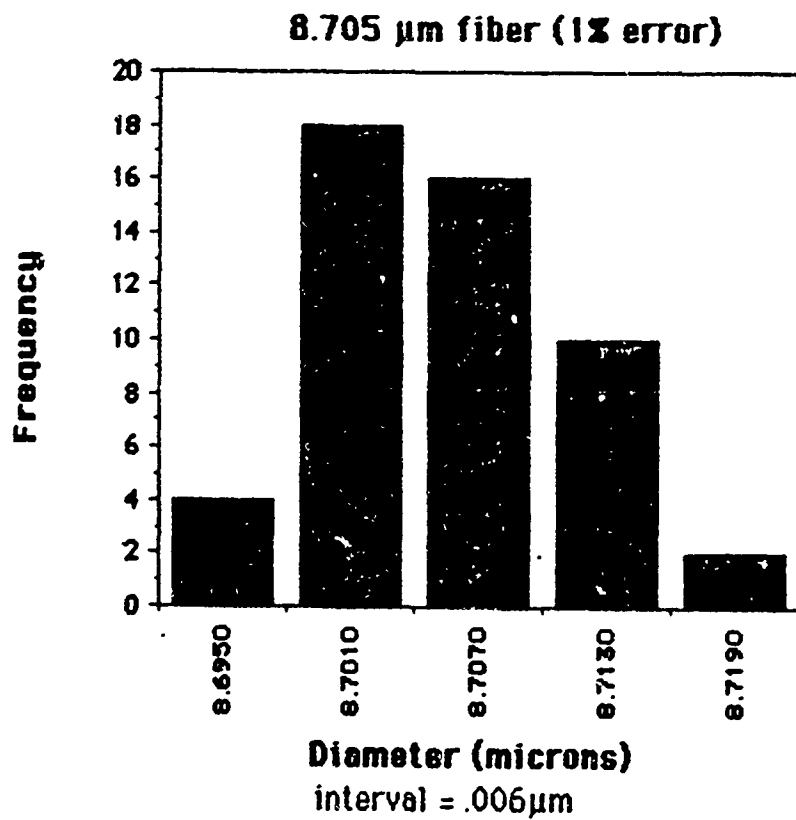


Figure 37. 8.705 μ m Fiber (1% error)

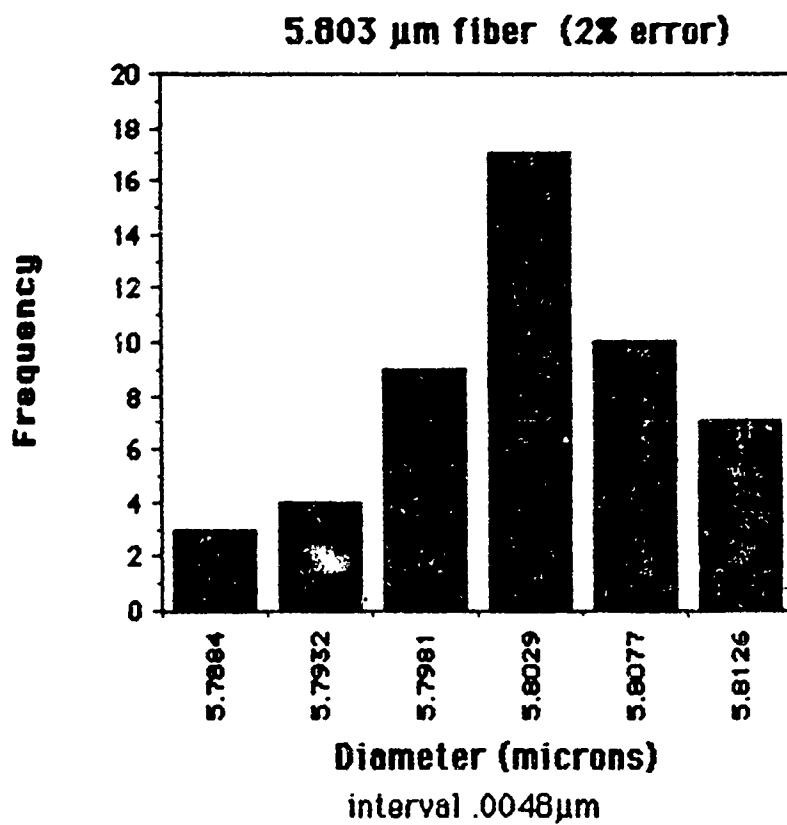


Figure 38. 5.803 μ m Fiber (2% error)

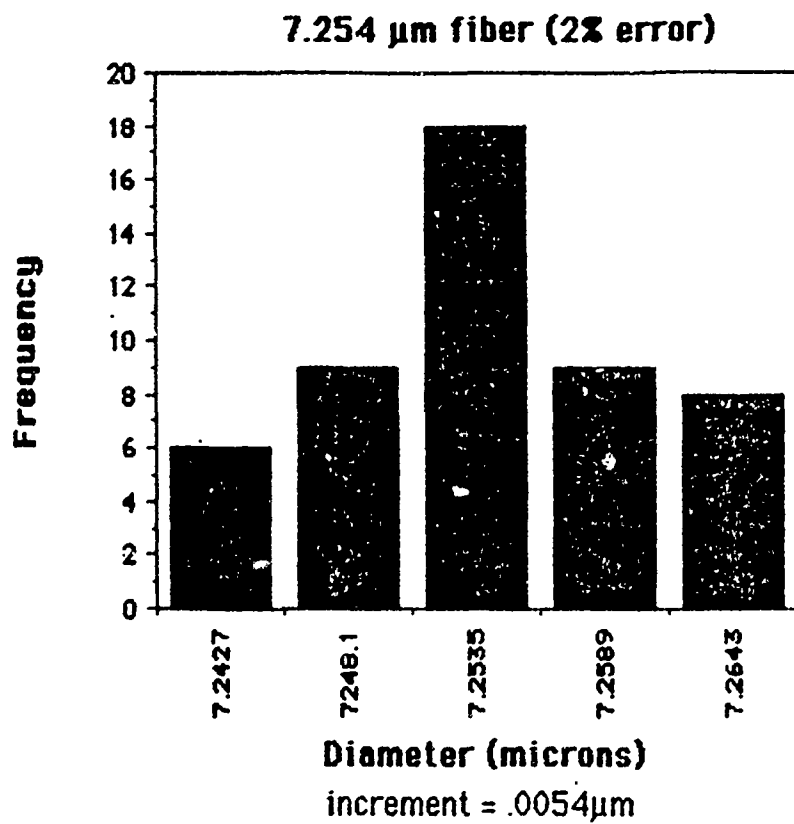


Figure 39. 7.254 μm Fiber (2% error)

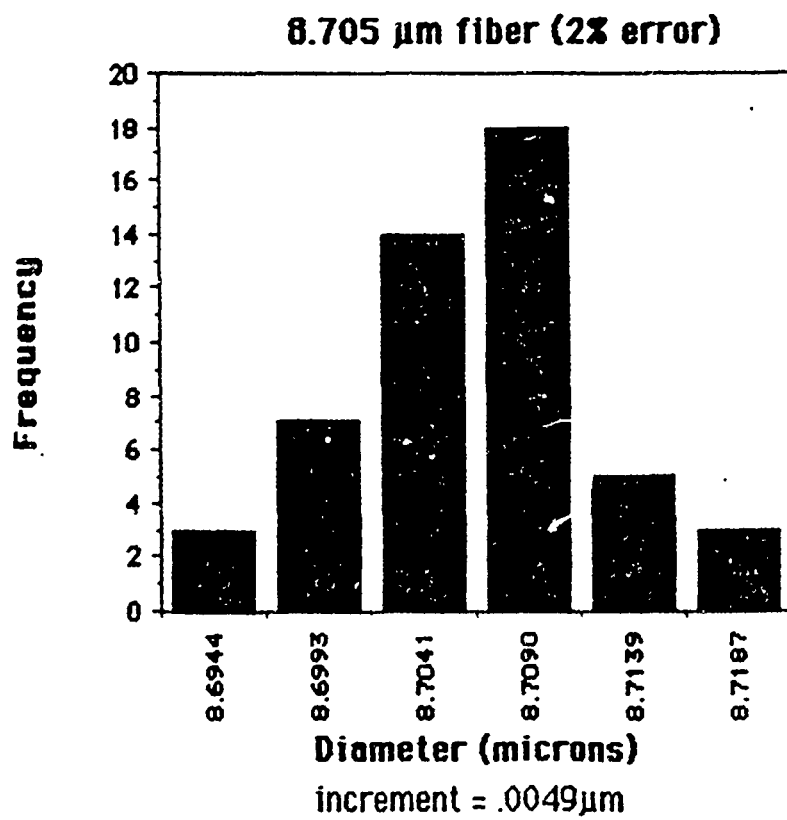


Figure 40. 8.705 μm Fiber (2% error)

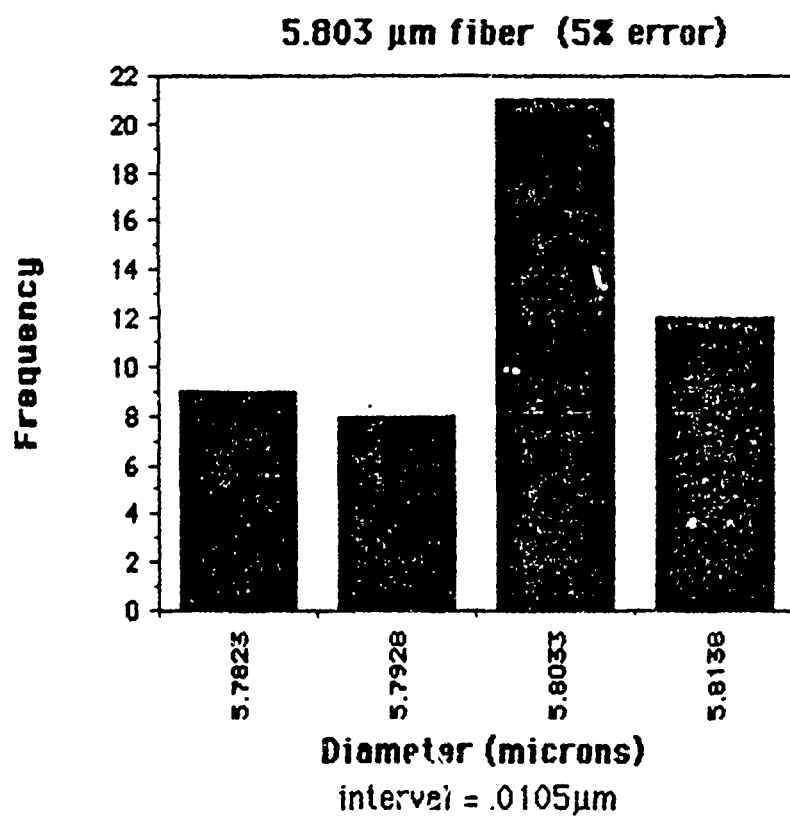


Figure 41. 5.803 μm Fiber (5% error)

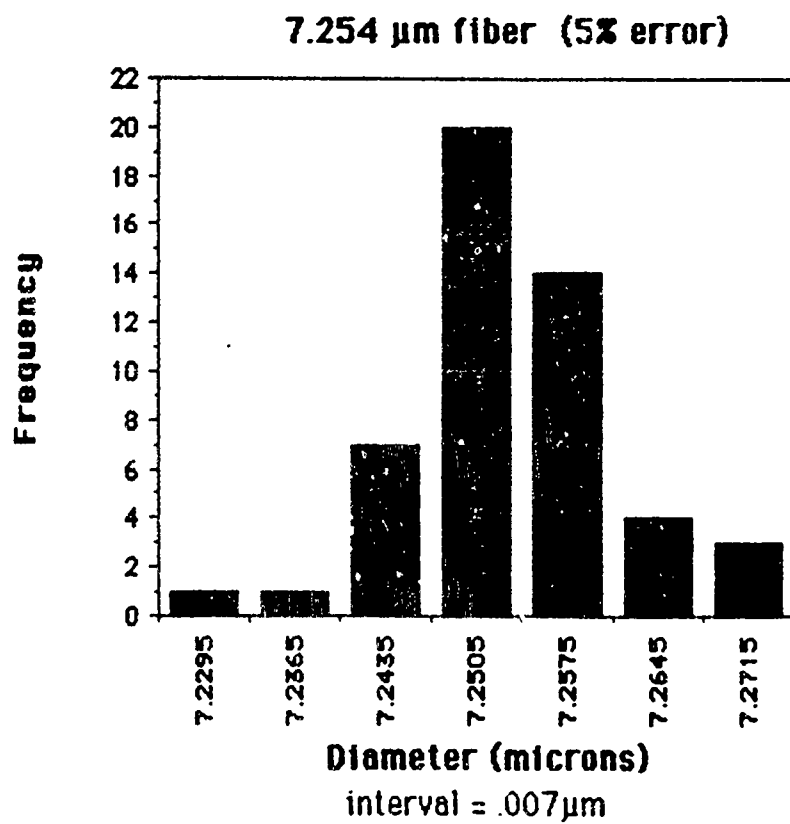


Figure 42. 7.254 μm Fiber (5% error)

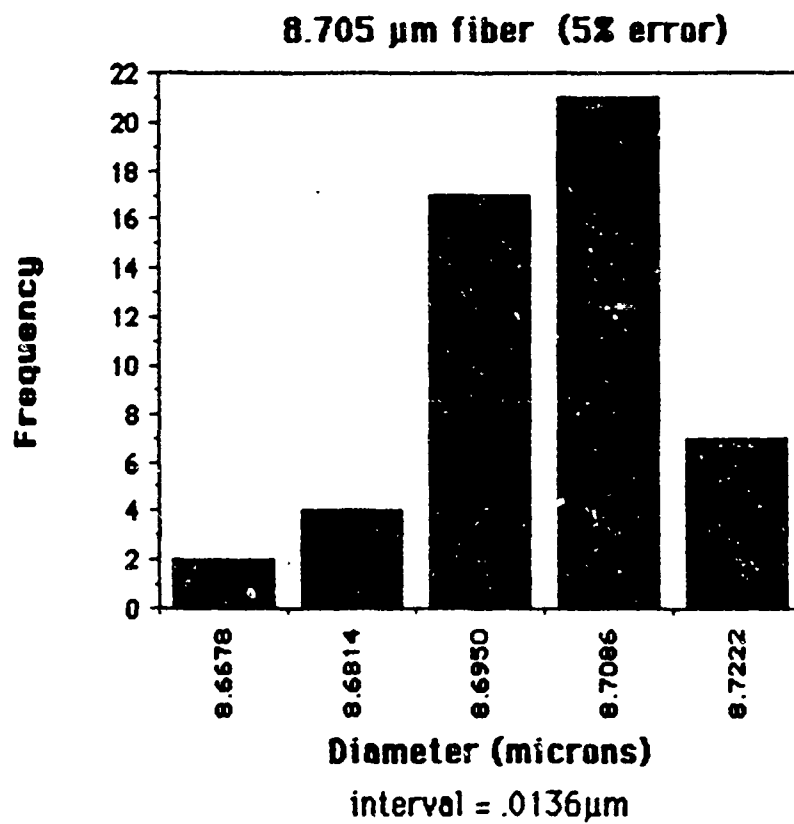


Figure 43. 8.705 μm Fiber (5% error)

A. ACCURACY VERSUS RESOLUTION

The histograms show the accuracy and the resolution of the method. The accuracy is associated with the largest spike, and related to the size of the interval called the resolution. The resolution is the ability of the routine to "see" a difference between two different fibers. For example, if the resolution is $.005\mu\text{m}$ the method does not discriminate between $8.705\mu\text{m}$ and $8.700\mu\text{m}$. Table 2 shows accuracy versus resolution for the results.

Table 2. ACCURACY VERSUS RESOLUTION

ERROR	DIAMETER μm	RESOLUTION	ACCURACY (Res/dact) %
1	5.803	.004	.069
	7.254	.0042	.058
	8.705	.0060	.069
2	5.803	.0048	.083
	7.254	.0054	.074
	8.705	.0049	.056
5	5.803	.0105	.181
	7.254	.0070	.096
	8.705	.0136	.156

The data show a decrease in accuracy and resolution as error is increased. It is evident in most cases that the 7.254 μ m results are better because it was the "tuned" diameter. The only exception is the accuracy for the 8.705 μ m fiber (2% error) is better than the 7.254 μ m fiber. Overall, the largest error is .18 percent which is less than one half of the error associated with the manual laser diffraction method.

B. ERROR

There are two contributions to error in this simulation.

The first can result from programming/calculation errors. Many trial runs of the software were taken to minimize the likelihood of this kind of error.

The next type of error is the digitizing error encountered in an actual experiment. This error is simulated based on the maximum intensity of the profile curve, in the region of interest, to apply random error equally to all points. Had the random error been based on each point, points with less intensity would have less error, and points with higher intensity more error, which is inconsistent with the physical digitizing process. Using the maximum intensity avoided such a condition but it cannot be ascertained that this is the optimal representation of the physical system.

VIII. CONCLUSIONS

The results of the simulation are encouraging. The largest error is .18% or less than one half of the manual methods. Because the programs were carefully developed and tested it is unlikely they contributed to the error. Also, much effort was directed towards accurate simulation of the physical system so that the results would reflect what can be expected from the actual experimental measurements.

The simulation demonstrates an increase in accuracy two to ten times better than that currently possible by making manual measurements with laser diffraction. The method also lends itself to automation which makes it attractive for quality control purposes and research for materials development.

IX. RECOMMENDATIONS

This study has shown the feasibility of computer aided diameter measurements. There are many directions future work can take.

A. SOFTWARE.

More development and testing of the software could result in increased accuracy. It would also be valuable to implement the software on a small computer (like the Macintosh) to allow real time processing of actual data.

B. HARDWARE.

There remain some hardware considerations which must be resolved. The biggest of these, perhaps, is the accurate positioning of the Micron Eye array in the direction perpendicular to the laser beam. In an effort to increase the resolution and accuracy of the problem, the system may benefit from two Micron Eyes.

APPENDIX A. FRAUNHOFER DIFFRACTION THEORY

The following is a brief discussion of Fraunhofer diffraction theory with emphasis on aspects of the theory which relate to this research.

A. FRAUNHOFER DIFFRACTION

Fraunhofer diffraction (Figure 44) results when light approaches and leaves an obstacle or aperture in the form of plane wavefronts. [Ref. 4.p. 176] The light source and the plane of observation in effect are at infinity. A collimated laser beam is ideally capable of Fraunhofer diffraction because its beam consists of parallel rays advancing in phase.

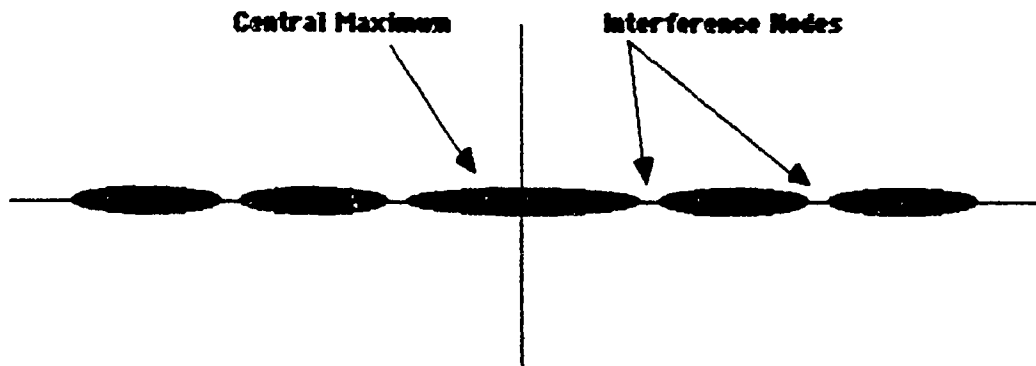


Figure 44. Typical Single Slit Diffraction Pattern

B. THE CLASSICAL SINGLE SLIT EXPERIMENT

The simplest demonstration of Fraunhofer diffraction is the single slit experiment. (See Figure 45) Parallel, collimated light passes through a slit of width a . The diffraction pattern is visible on a screen located a distance L from the slit. An observer at point P , moving across the screen, sees a succession of maximum and minimum intensity points. These extrema are the result of constructive and destructive interference of the light. For example, a minimum occurs when the angle θ produces a phase difference of one wavelength between the rays at the upper and lower edges of the slit. Thus, minima occur whenever

$$a \sin(\theta) = m\lambda, \text{ where } m = 1, 2, 3, \dots \quad (\text{A.1})$$

These minima are referred to as interference nodes. (For further discussion of this subject, see Meyer-Arendt, [Ref. 4].)

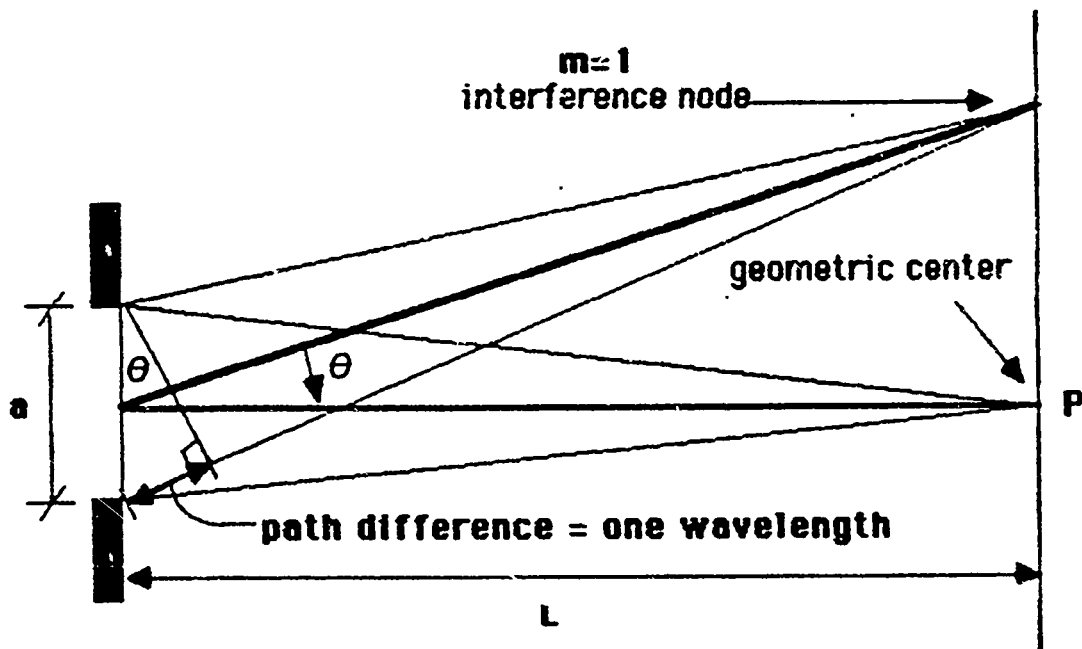


Figure 45. Single Slit Path Difference Relation to the Interference Node

1. Diffraction Minima

Examination of equation (A.1) shows that as the slit becomes narrower the angle θ becomes larger. As this theory is extended to approximate the diffraction phenomena of an obstruction (a fiber), one can expect short distances between interference nodes for larger fibers and greater distances between nodes for fibers of smaller diameters.

Another important point concerns the distance between minima. It appears the interference nodes are equidistant. This is true only within the limits of the small angle approximation. The distances between interference nodes actually increases as one moves outward from the central maximum by the relation:

$$\theta_{\min} = \sin [m\lambda/d] \quad (A.2)$$

2. Diffraction Maxima

The diffraction maxima are not located midway between minima. The locations of the maxima can be derived as by Meyer-Arendt [Ref. 7:p. 220]. These occur whenever the derivative of the intensity is equal to zero:

$$\begin{aligned} dI/dB &= dI/dB [I_0 (\sin B/B)^2] = 0 \\ &= 2I_0 \sin B/B [-\sin B/B^2 + \cos B/B] \end{aligned}$$

$$\text{or whenever: } B = \tan B \quad (A.3)$$

$y = \tan \beta$ and $y = \beta$. (See Figure 46) The maxima are displaced slightly from center towards the central maximum. Much further away from the central maximum, the maxima are nearly halfway between minima.

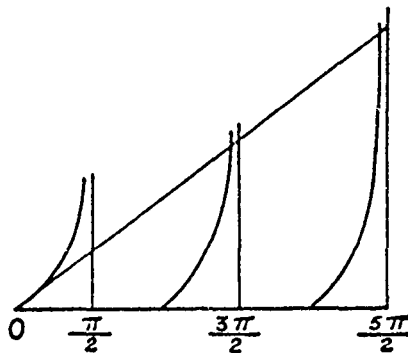


Figure 46. Locations of the Diffraction Maxima

C. FRAUNHOFER DIFFRACTION AND THE FOURIER TRANSFORM

The foregoing discussion centered on the Fraunhofer diffraction due to a slit. The mathematics of the slit example are simple and provide insight into diffraction physics. A more elegant derivation of Fraunhofer diffraction shows that the diffraction pattern of an object is the Fourier transform of that object. [Ref. 9:p. 174]

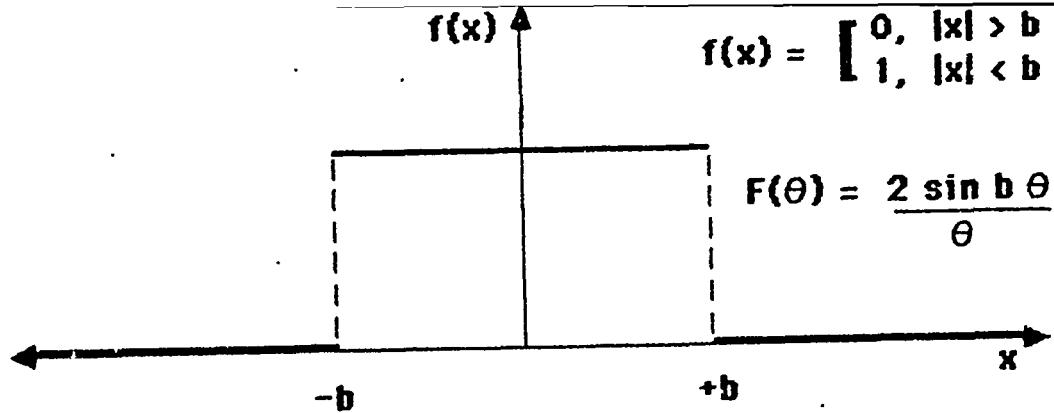


Figure 47. Fourier Transform for the Single Slit

Thus, $F(\theta)$ describes the amplitude of the diffraction pattern, and $[F(\theta)]^2$ represents the intensity.

Modeling the transform for the obstruction is more complicated. consider the complement of the slit transform: $g(x) = 1 - f(x)$.

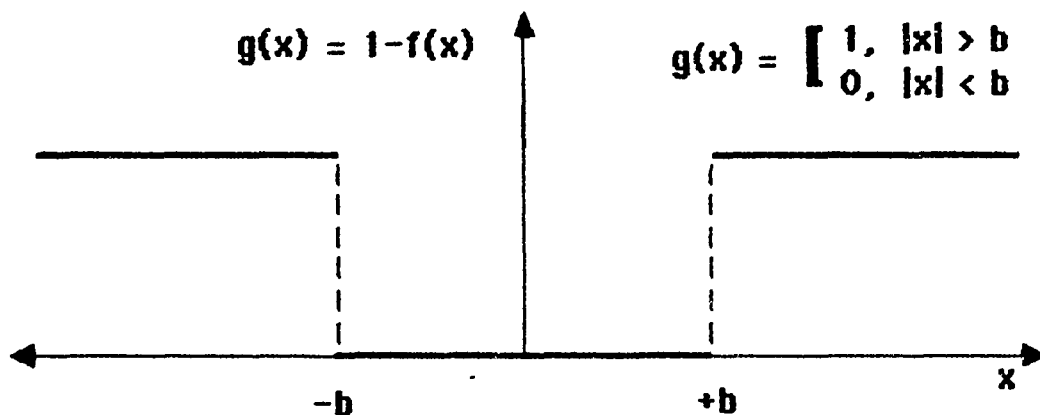


Figure 48. Complement of the Fourier Slit Transform

This results in the form $[\infty - 2\sin(b\theta)/\theta]$ which is not transformable.

An alternative is to use a substitute function $h(x) = g(x) - f(x)$. Physically, this is approximating the obstruction as two parallel slits:

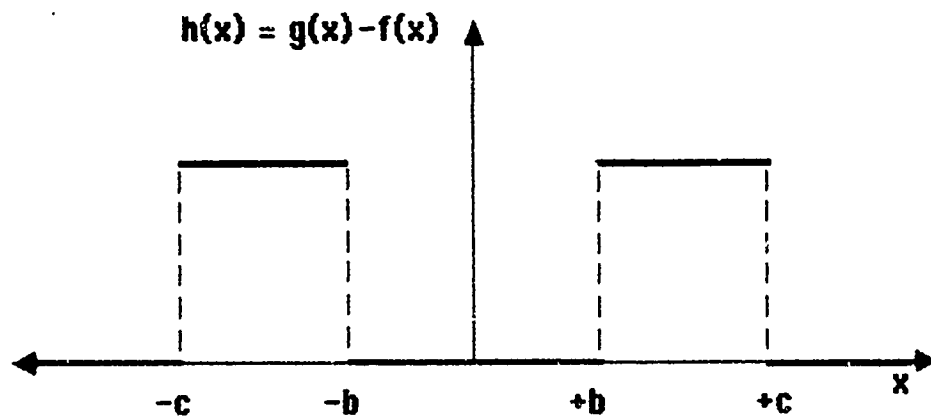


Figure 49. Fourier Transform for Two Parallel Slits

which has the solution:

$$H(\theta) = (2\sin c\theta)/\theta - (2\sin b\theta)/\theta$$

where c would be large, but not infinite.

This is still a crude approximation which shall be improved upon in the next section.

D. REJECTION OF THE SLIT APPROXIMATION

In their paper titled "Fiber Diameter Measurement by Laser Diffraction" [Ref. 3:p. 1378], Perry, Ineichen, and Eliasson conclude that the diffraction pattern of a real fiber is sufficiently different from that of a slit to warrant the slit approximation being treated with caution.

Further, they recommend a solution presented by Kerker [Ref.5:p. 260] which has been adopted in this study. Kerker's solution assumes the fiber is perfectly reflecting (i.e., the reflective index $m=\infty$), and while this is not completely true, Perry, et al., [Ref. 3:p. 1378] indicate some degree of absorption is not likely to be significant.

E. INTENSITY EQUATION FOR A REAL FIBER

Kerker [Ref. 5:p. 260] gives the scattered intensity relation for a real fiber:

$$I/I_0 = (2/K_0 L \pi) \left| b_0 + 2 \sum b_n \cos(n\theta) \right|^2 \quad (A.4)$$

where θ = the scattering angle

$$K_0 = 2\pi / \lambda \quad (\lambda = \text{laser wavelength})$$

$$b_n = J_n(\alpha) / H_n^{(2)}(\alpha)$$

and $\alpha = \pi d_f / \lambda$ (d_f = fiber diameter)

$J_n(\alpha)$ are Bessel functions of the first kind,

$H_n^{(2)}(\alpha)$ are Hankel functions of the second kind.

The real fiber equation (A.4) is somewhat obscure in its compact form. It can be shown that:

$$I/I_0 = (2/K_0 L \pi) \left[(r_0 + 2 \sum r_n \cos(n\theta))^2 + (s_0 + 2 \sum s_n \cos(n\theta))^2 \right] \quad (A.5)$$

where $r_n = J_n^2(\alpha) / [J_n^2(\alpha) + Y_n^2(\alpha)] \quad (A.6)$

and $s_n = J_n(\alpha) Y_n(\alpha) / [J_n^2(\alpha) + Y_n^2(\alpha)] \quad (A.7)$

Now, the intensity ratios for any θ location can be calculated for any diameter fiber.

1. Sensitivity of the Results to the Number of Bessel Terms

The calculation of Intensity Ratios requires the computation of r_n and s_n Bessel terms, equations (A.6) and (A.7). Here the phrase "Bessel terms" indicates the algebraic combinations of the J_n and Y_n Bessel functions.

a. Two competing phenomena

There exist two competing phenomena which govern the number of Bessel terms to be used in the calculations. The first requires a minimum number of terms for accuracy. The second, limits the number of terms so the Y functions do not cause an underflow error during computation.

(1) Minimum Number of Terms. As in any series, there is a minimum number of terms required for computational accuracy. Figure 50 shows the effect of the number of Bessel terms computed for seven curves, all with a diameter of eight microns.

Note that the 43, 50, 75, and 86 term curves are nearly identical and the curves with fewer than 43 terms are decreasing towards a smooth line. This research, indicates that 50 terms returns four digit accuracy for diameters ranging from 5 to 10 microns.

(2) Maximum Number of Terms. The maximum number of terms depends on the value of α . As the diameter decreases, so does α . This in turn produces very large values of $Y_n^2(\alpha)$ (in the r_n and s_n denominator) which causes an underflow error. For the diameter range considered in this research, underflow was not a problem. In one instance, below 5 microns, it was found the number of Bessel terms had to be reduced to 43 to prevent underflow. The effects of the minimum number of terms was not investigated at this smaller diameter range.

INTENSITY PROFILE

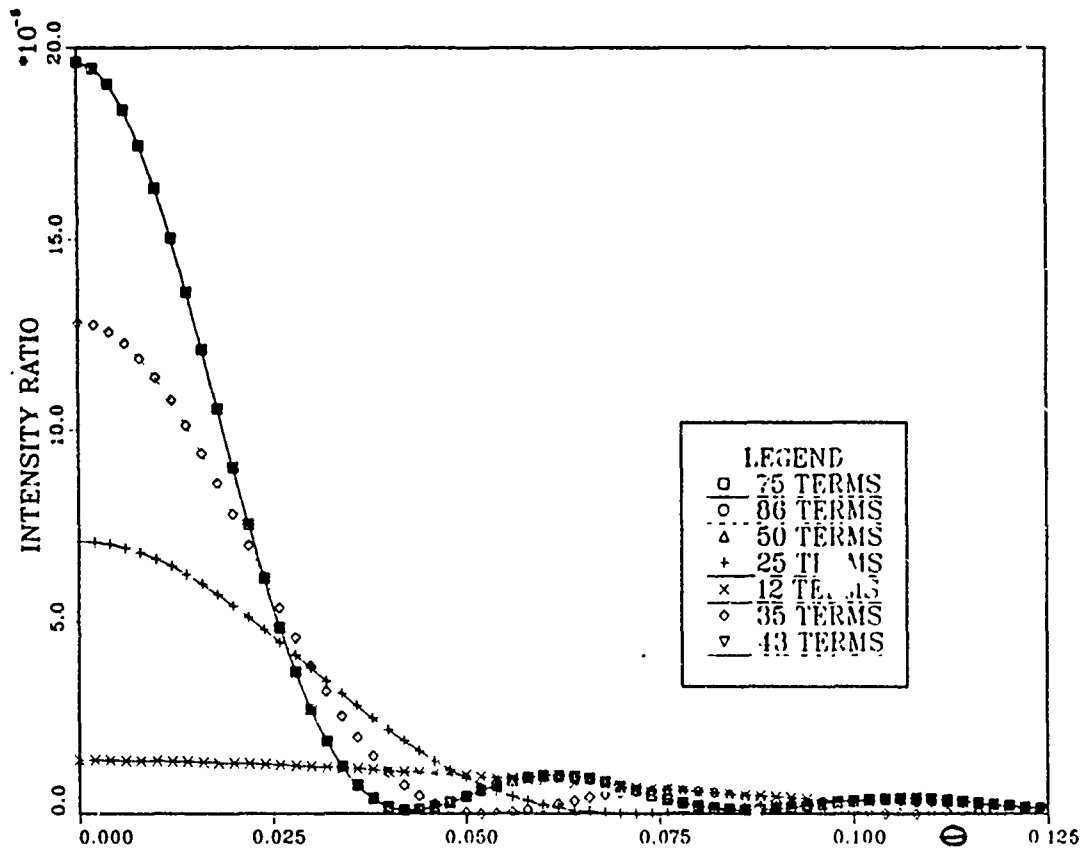


Figure 50. Effect of Number of Bessel Terms

2. Effect of Different Diameters

Recall that the diffraction pattern for a slit showed that as the diameter decreased, the interference nodes moved away from the center of the pattern. It is interesting to note that the pattern for a real fiber behaves the same way. (See Figure 51)

INTENSITY PROFILES

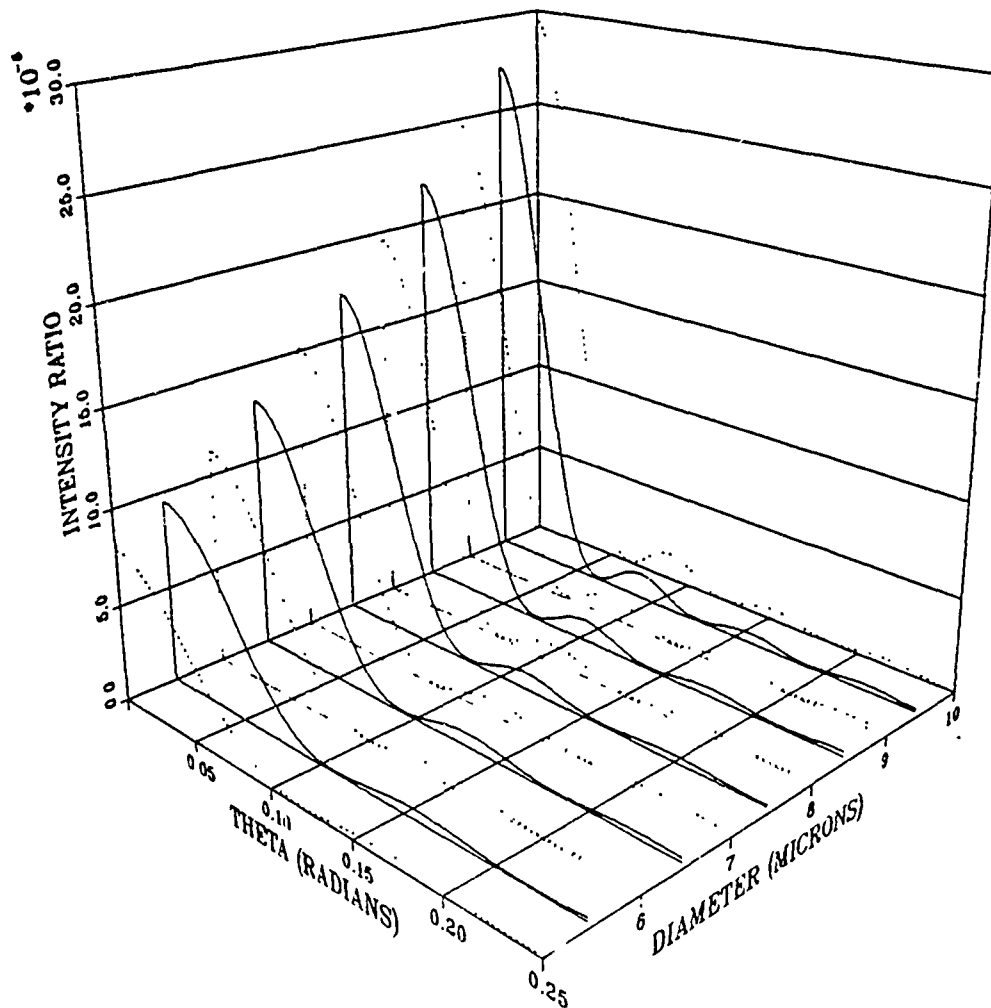


Figure 51. Effect of Different Diameters

APPENDIX B. COMPUTER PROGRAMS

The following is a list of programs discussed in this Appendix:

DATAMAKR

DIAFIND

EXPOSURE

The programs are written in Waterloo Fortran IV (WATFIV) and run on the Naval Postgraduate School's IBM 360 computer.

A. FORMAT OF DATA

All data is formatted using exponential notation. The most frequently manipulated files are those containing theta locations and intensity ratios. The format for these files is: (1X, E17.10, 1X, E17.10). In WATFIV all data files must be of filetype "WATFIV".

To compile and run a program on the IBM 360 type " WATFIV
PROGNAME DATAFILE *(XTYPE", where PROGNAME is the filename of the
program and DATAFILE is the filename of the data file.

B. COMPUTER PROGRAMS

This appendix presents the various computer programs and outlines their logic.

1. DATAMAKR

DATAMAKR generates the data used in the simulation. The equation for computing the Intensity Ratios of the diffraction pattern for any value of theta is:

$$I/I_0 = (2/K_0 L \pi) \left| b_0 + 2 \sum b_n \cos(n\theta) \right|^2 \quad (A.4)$$

where θ = the scattering angle

$$K_0 = 2\pi / \lambda \quad (\lambda = \text{laser wavelength})$$

$$b_n = J_n(\alpha) / H_n^{(2)}(\alpha)$$

and $\alpha = \pi d_f / \lambda$ (d_f = fiber diameter)

$J_n(\alpha)$ are Bessel functions of the first kind,

$H_n^{(2)}(\alpha)$ are Hankel functions of the second kind.

All computations begin by calculating the required number of Bessel terms. Two NONIMSL subroutines are called: BESJ for the $J_n(\alpha)$ and

BESY for the $Y_n(\alpha)$. Note: should double precision be desired, the NONIMSL subroutine BINT will return double precision values for the J_n and Y_n .

The Bessel function values are stored in an vector $J(I)$ and $Y(I)$, and are used to calculate values of $R(I)$ and $S(I)$. Next, the matrix of cosines is constructed. The size of this matrix is M by K , where $N = M-1$ and N is the number of Bessel terms. K is the number of theta locations. Values of theta at each location have previously been stored in an array called $T(K)$.

To visualize the program's calculations, the matrices symbolic of these calculations are sketched. (See Figure 52) Note that r_0 and s_0 are outside the summation term in equation (A.1) and therefore will not be multiplied with any cosine terms. Since array subscripts must be designated with a nonzero value, r_0 and s_0 will be represented by $r(1)$ and $s(1)$.

After multiplying the two matrices, it is necessary to complete the summation by summing the columns in the matrix. This results in an N term value for each value of theta. A straightforward calculation then yields the intensity ratios. The intensity ratios are stored in an array with their corresponding theta locations.

$$\begin{bmatrix} r_2 \\ r_3 \\ r_4 \\ \vdots \\ r_m \end{bmatrix} \times \begin{bmatrix} \cos \theta_1 & \cos \theta_2 & \dots & \cos \theta_k \\ \cos 2\theta_1 & \cos 2\theta_2 & & \cos 2\theta_k \\ \cos 3\theta_1 & \cos 3\theta_2 & & \cos 3\theta_k \\ \vdots & \vdots & & \vdots \\ \cos(m-1)\theta_1 & \cos(m-1)\theta_2 & \dots & \cos(m-1)\theta_k \end{bmatrix}$$

$$[R] \times [C] = \begin{bmatrix} r_2 c_{11} & \dots & r_2 c_{1k} \\ r_3 c_{21} & & \\ r_4 c_{31} & & \\ \vdots & & \vdots \\ r_m c_{m-1,1} & \dots & r_m c_{m-1,k} \end{bmatrix}$$

↓

$$\sum_{n=1}^m r_n \cos(n\theta_k)$$

Figure 52. DATAMAKR Matrix Algebra

The logic of DATAMAKR is:

Input -----> * Bessel terms to be computed
 diameter of the fiber
 screen to fiber distance, L
 array of theta location values

Calculate: R_n and S_n using BESJ and BESY

Produce the Matrix of Cosines

Produce the Matrix of Products

Sum the columns of the Product Matrix

Compute and output the Intensity Ratios

2. DIAFIND

This program finds the diameter of a fiber through an iterative process of residual comparison. The program accepts the data which has been output by the program EXPOSURE. The user is prompted for K and d_i . K is the number of theta values the program should expect and d_i is the initial guess of the fiber diameter (in microns).

The program first calculates intensity ratios at the diameter d_i , corresponding to the input theta locations. The difference between the input intensity ratios and those associated with d_i is called the residual. The program calculates another set of intensity ratios based on a new diameter $d_i + \Delta d_i$, where Δd_i is a small increment of diameter (usually .05 microns to start). The intensity ratios calculated using $d_i + \Delta d_i$ are compared with the input intensity ratios to give a second residual. The residuals are compared and program logic determines whether or not the Δd increment is producing convergence to the actual diameter. The initial guess diameter is incremented and decremented as necessary until a desired level of accuracy is achieved.

A key to understanding the convergence process is the residual curve in Figure 53. It is important that the initial guess, d_i , be fairly close to the actual diameter.

For example, the residual curve in Figure 53 is for an actual diameter of 7 microns. If d_i is greater than 9 microns, the program will not converge to the correct diameter, but rather to a diameter just above 10 microns.

It is hard to define exactly the limits of d_i for any given actual diameter. Figure 54 is a residual curve for 5 microns and shows an upper

limit of 9 microns for d_i . A thorough study to define limits for d_i has not been conducted, although convergence has always been attained by guessing d_i within ± 1 micron for diameters ranging from 5 to 9 microns.

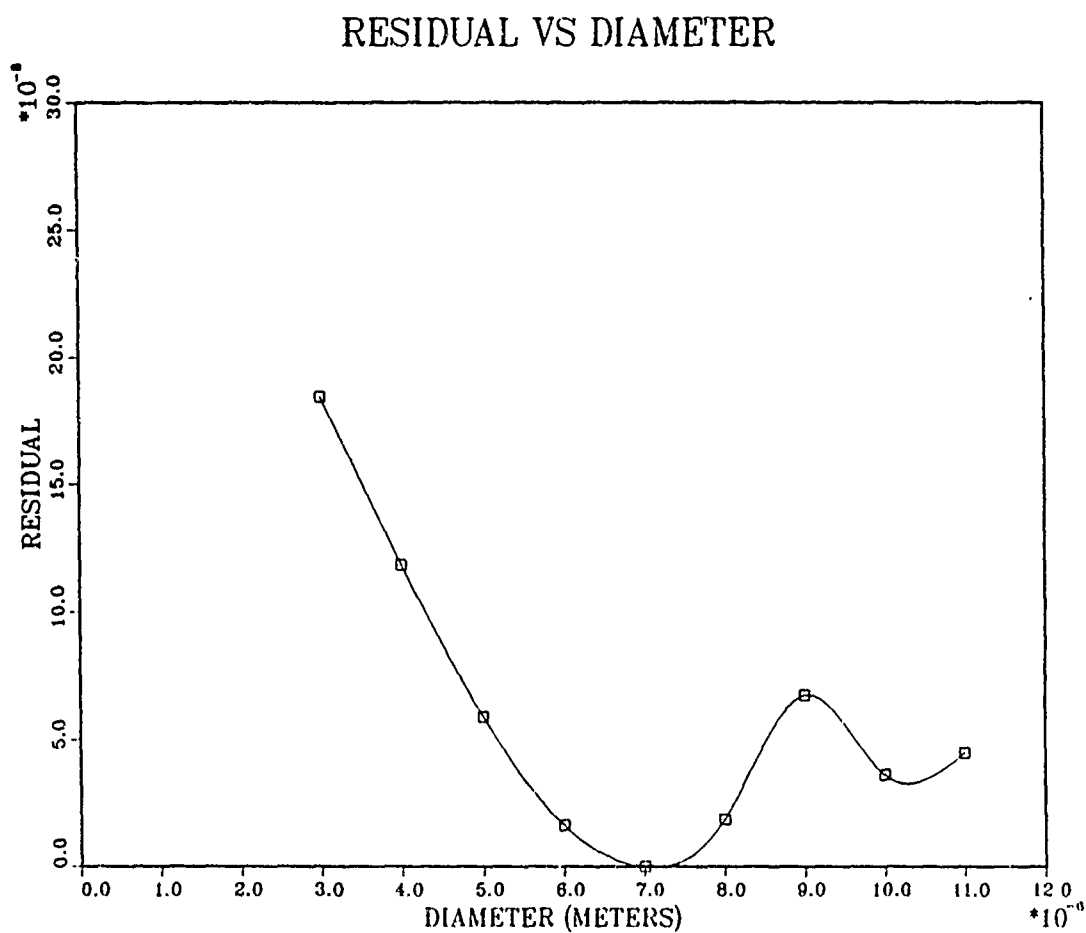


Figure 53. Residual Versus Diameter for 7 μ m Fiber

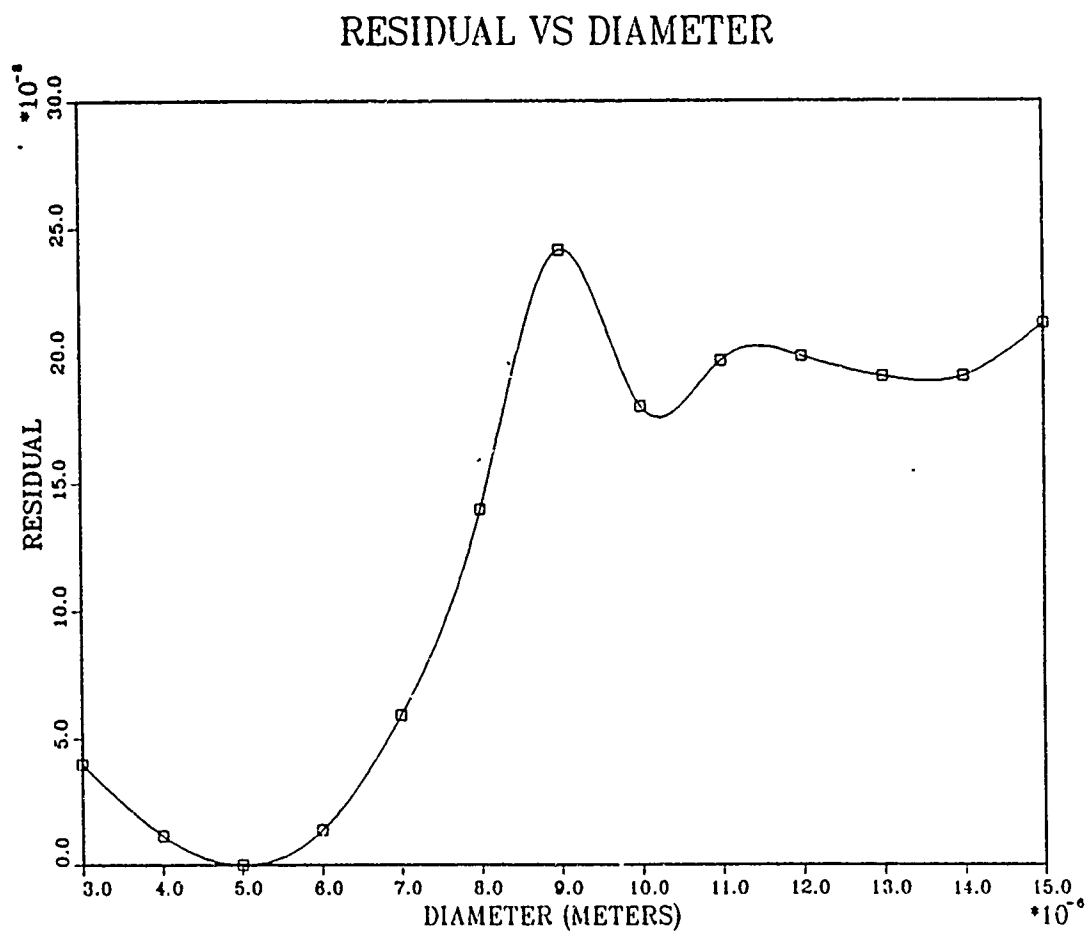


Figure 54. Residual Versus Diameter for 5 μ m Fiber

3. EXPOSURE

EXPOSURE simulates the operation of the Micron Eye by taking a photograph of intensity ratio data. EXPOSURE reads in the perfect data generated by DATAMAKR and digitizes the data with respect to a threshold intensity ratio.

The optimum intensity ratio for an exposure is termed the **threshold intensity ratio**. The threshold intensity ratio is located where the absolute value of the derivative of the intensity ratio with respect to theta is a maximum. This assures that the threshold intensity ratio is located in a region of the curve which is closest to a straight line. This reduces the effects of subsequent interpolation errors.

The threshold intensity ratio is calculated by the subroutine DERIV. Since the input intensity profile curve will have at least three maximum derivative points, DERIV calculates the average of the three intensity ratios. This average is then passed to the calling program, EXPOSURE.

EXPOSURE searches the intensity ratios and compares them with the value of the threshold intensity ratio. This process corresponds to the Micron Eye addressing a pixel and comparing its voltage to the threshold voltage. If an intensity ratio is greater than the threshold value, the ratio is assigned a digital value of 1. If the intensity ratio is less than the threshold value, the ratio is assigned a digital value of 0.

The digitized data is then searched to find the theta locations at which the digital intensities change from 0 \rightarrow 1, or from 1 \rightarrow 0. The theta locations are averaged to produce a theta location which is very close to the threshold intensity. Because this averaging process is occurring in the regions of steepest slope, error is assumed to be minimized since the curve can be approximated as a straight line (refer to Figure 30 in Chapter 6).

EXPOSURE provides the user with the option of introducing error into the perfect data. The program prompts the user to input the desired error and calls the subroutine RANDOM. RANDOM introduces random error into the intensity ratios and returns the imperfect data to EXPOSURE. EXPOSURE digitizes the imperfect data and searches for the occurrences where 0 \rightarrow 1 and 1 \rightarrow 0. Imperfect data will have many more occurrences of the digital intensities changing from 1 \rightarrow 0 and 0 \rightarrow 1. EXPOSURE will average the theta locations if they are in the same location (i.e., within ± 0.005 radians). This method has been tested for random error up to 5 percent.


```

$JOB
C C C C C C C
      DATAK.  THIS PROGRAM IS DESIGNED TO PRODUCE DATA FOR USE
      BY THE SIMULATION PROGRAM "DIAFIND".
      USER MUST EDIT PROGRAM TO CHANGE THE VALUE OF 'L'
      AND THE INCREMENT VALUE FOR THETA.

      INTEGER I, N, M, K
      REAL DIAM, LAMBDA, L, KNOT, CONST, PI, D, X, J, DIA, T, B
      DIMENSION J(100), Y(100), R(100), S(100),
      & IERY(100), IERJ(100), DENOM(100), SC(100,200), RSUM(200),
      & T(200), C(100,200), RC(100,200), EYE(200)
      & SSUM(200), EYE(200)
      INPUT:
      DIAMETER IS THE DIAMETER OF THE FIBER.
      LAMBDA IS THE WAVELENGTH OF THE LASER.
      L IS THE DISTANCE OF THE SAMPLE FIBER FROM THE
      DIFFRACTION PATTERN. ALL LENGTHS ARE IN METERS.

      CALL FRTCMS( 'CLRSCRN ' )
      WRITE(6,3) ' '
      FORMAT(1,3) ' '
      WRITE(6,4) ' '
      FORMAT(1,4) ' '
      READ, DIA
      B IS THE STARTING POINT OF THE THETA VALUES
      WRITE(6,10)
      FORMAT(/,1X, 'INPUT STARTING POINT OF DATA (RADS)...')
      READ, B

      DIAM = DIA * (1D-06)
      PI = 3.141592654
      LAMBDA = 632.800D-09
      L = .030
      D IS THE ACCURACY PARAMETER FOR THE BESJ SUBROUTINE:
      D = .000001
      M = 50
      K = 100
      X = (PI * DIAM) / LAMBDA
      KNOT = (2.0D0 * PI) / LAMBDA
      CONST = 2.0D0 / (KNOT * L * PI)

```



```

C      RSUM(N) = RSUM(N) + RC{ I-1, N }
C      SSUM(N) = SSUM(N) + SC{ I-1, N }
C      CONTINUE
599 CONTINUE
600 CONTINUE
C*****
C      FINAL CALCULATION .....
C      DO 700 N=1, K
C      EYE(N)=CONST*( ( R(1)+2*RSUM(N) )**2 + ( S(1)+2*SSUM(N) )**2 )
C      CONTINUE
700 CONTINUE
C*****
C      OUTPUT MODULE ....
C      PRINT 1
C      FORMAT ('1')
C
C      PRINT 1 FOR 'M, 'BESEL COEFFICIENTS & DIAMETER OF', DIA, 'MICRONS'
C      PRINT, M, 'BESEL COEFFICIENTS & DIAMETER OF', DIA, 'MICRONS'
C      DO 801 N=1, K
C      WRITE(8,800) T(N), EYE(N)
C      FORMAT(1X, E17.10, 1X, E17.10)
800 CONTINUE
801 CONTINUE
C
C      STOP
C      END
C*****
C      SUBROUTINES FOR CALCULATION OF THE BESSEL FUNCTIONS.
C      SUBROUTINE BESJ

```

```

PURPOSE
  COMPUTE THE J BESSEL FUNCTION FOR A GIVEN ARGUMENT AND ORDER

USAGE
  CALL BESJ(X,N,BJ,D,IER)

DESCRIPTION OF PARAMETERS
  X  -THE ARGUMENT OF THE J BESSEL FUNCTION DESIRED
  N  -THE ORDER OF THE J BESSEL FUNCTION DESIRED
  BJ -THE RESULTANT J BESSEL FUNCTION
  D  -REQUIRED ACCURACY
  IER-RESULTANT ERROR CODE WHERE
      IER=0 NO ERROR
      IER=1 N IS NEGATIVE
      IER=2 X IS NEGATIVE OR ZERO
      IER=3 REQUIRED ACCURACY NOT OBTAINED
      IER=4 RANGE OF N COMPARED TO X NOT CORRECT (SEE REMARKS)

REMARKS
  N MUST BE GREATER THAN OR EQUAL TO ZERO, BUT IT MUST BE
  LESS THAN
    20+10*X-X** 2/3  FOR X LESS THAN OR EQUAL TO 15
    90+X/2           FOR X GREATER THAN 15

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
  NONE

METHOD
  RECURRENCE RELATION TECHNIQUE DESCRIBED BY H. GOLDSTEIN AND
  R.M. THALER, RECURRENCE TECHNIQUES FOR THE CALCULATION OF
  BESSEL FUNCTIONS, M.T.A.C. V.13 PP.102-108 AND I.A. STEGUN
  AND M. ABRAMOWITZ, GENERATION OF BESSEL FUNCTIONS ON HIGH
  SPEED COMPUTERS, M.T.A.C., V.11, 1957, PP.255-257
  .....

SUBROUTINE BESJ(X,N,BJ,D,IER)

  BJ=.0
  IF(N) 10,20,20
  IER=1
  10 RETURN
  20 IF(X) 30,30,31
  30 IER=2
  RETURN
  31 IF(X-15.) 32,32,34
  32 NTEST=20.+16.*X-X** 2/3
  GO TO 36
  36
  .....

```

```

34 NTEST=90.+X/2.
36 IF(N-NTEST)40,38,38
38 IER=4
40 RETURN
40 IER=0
  N1=N+1
  BPREV=.0
  COMPUTE STARTING VALUE OF M
  IF(X-5.)50,60,60
  MA=X+6.
  GO TO 70
  MA=1.4*X+60./X
  MB=N+IFIX(X)/4+2
  MZERO=MAXO(MA,MB)
  SET UPPER LIMIT OF M
  MMAX=NTEST
  100 DO 190 M=MZERO,MMAX,3
  SET F(M),F(M-1)
  FM1=1.OE-28
  FM=.0
  ALPHA=.0
  IF(M-(M/2)*2)120,110,120
  110 JT=-1
  GO TO 130
  120 JT=1
  130 M2=M-2
  DO 160 K=1,M2
  MK=M-K
  BMK=2.*FLOAT(MK)*FM1/X-FM
  FM=FM1
  FM1=BMK
  IF(MK-N-1)150,140,150
  140 BJ=BMK
  150 JT=-JT
  S=1+JT
  ALPHA=ALPHA+BMK*S
  BMK=2.*FM1/X-FM
  IF(N)180,170,180
  170 BJ=BMK
  180 ALPHA=ALPHA+BMK
  BJ=BJ/ALPHA
  IF(ABS(BJ-BPREV)-ABS(D*BJ))200,200,190

```

```
190 BPREV=BJ
    IER=3
200 RETURN
    END
```

```

IF(N)180,10,10
IER=0
IF(X)190,190,20
BRANCH IF X LESS THAN OR EQUAL 4
20 IF(X-4.0)40,40,30
    COMPUTE Y0 AND Y1 FOR X GREATER THAN 4
30 T1=4.0/X
   T2=T1*T1
   P0=((-.0000037043*T2+.0000173565)*T2-.0000487613)*T2
   1 + (.00017343)*T2-.001753062)*T2+.3989423
   Q0=((-.0000032312*T2-.0000142078)*T2+.0000342468)*T2
   1 -.0000869791)*T2+.0004564324)*T2-.01246694
   P1=((-.0000042414*T2-.0000200920)*T2+.0000580759)*T2
   1 -.000223203)*T2+.002921826)*T2+.3989423
   Q1=((-.0000036594*T2+.00001622)*T2-.0000398708)*T2
   1 +.0001064741)*T2-.0006390400)*T2+.03740084
   A=2.0/SQRT(X)
   B=A*T1
   C=X-.7853982
   Y0=A*P0*SIN(C)+B*Q0*COS(C)
   Y1=-A*P1*COS(C)+B*Q1*SIN(C)
   GO TO 90
    COMPUTE Y0 AND Y1 FOR X LESS THAN OR EQUAL TO 4
40 XX=X/2
   X2=XX*XX
   T=ALOG(XX)+.5772157
   SUM=0.
   TERM=T
   Y0=T
   DO 70 L=1,15
   IF(L-1)50,60,50
50 SUM=SUM+1./FLOAT(L-1)
60 FL=L
   TS=T-SUM
   TERM=(TERM*(-X2)/FL**2)*(1.-1./FL*TS))
70 Y0=Y0+TERM
   TERM=XX*(T-.5)
   SUM=0.
   Y1=TERM
   DO 80 L=2,16
   SUM=SUM+1./FLOAT(L-1)
80 FL=L

```



```

      FL1=EL-1.
      TS=T-SUM
      TERM=(TERM*(-X2))/(FL1*FL1))*((TS-.5/FL)/(TS+.5/FL1))
80  Y1=Y1+TERM
      PI2=.6366198
      YO=PI2*YO
      Y1=-PI2/X+PI2*Y1
      CHECK IF ONLY YO OR Y1 IS DESIRED
90  IF(N-1)100,100,130
      RETURN EITHER YO OR Y1 AS REQUIRED
100 IF(N)110,120,110
110 BY=Y1
      GO TO 170
120 BY=YO
      GO TO 170
      PERFORM RECURRENCE OPERATIONS TO FIND YN(X)
130 YA=YO
      YB=Y1
      K=1
140 T=FLOAT(2*K)/X
      YC=T*YB-YA
      IE(ABS(YC)-1.0E70)145,145,141
141 IER=3
      RETURN
145 K=K+1
150 IF(K-N)150,160,150
      YA=YB
      YB=YC
      GO TO 140
160 BY=YC
170 RETURN
180 IER=1
      RETURN
190 IER=2
      RETURN
      END
CC $ENTRY

```

DIA FIND. THIS PROGRAM ACCEPTS THETA AND INTENSITY RATIO
 DATA AND PROCEEDS TO FIND THE DIAMETER CORRESPONDING TO THE
 DATA. USER IS PROMPTED FOR THE INITIAL GUESS OF THE DIAMETER
 WHICH MUST BE CLOSE TO THE ACTUAL DIAMETER OR THE PROGRAM MAY
 FIND THE WRONG DIAMETER. USER MUST MODIFY PROGRAM PRIOR TO BE
 RUNNING: K, L, AND M. K IS THE NUMBER OF DATA POINTS TO BE
 READ. L IS THE SCREEN TO FIBER DISTANCE IN METERS. M IS
 THE NUMBER OF BESSEL TERMS TO BE COMPUTED. (USUALLY 50, BUT
 MAY NEED TO BE SMALLER IF CALCULATING SMALL DIAMETERS,
 I.E. LESS THAN 5 MICRONS.)

INTEGER I, COUNT, FLAG, LOWER, UPPER, K, M, NEWDEL
 REAL T, DELTAD, BETA, R, DEE, TEST
 REAL INTGES, INTACT, L, ACTUAL
 DIMENSION DEE(100), R(100), T(100), Q(100)
 DIMENSION INTACT(100), INTGES(100)

M IS THE NUMBER OF BESSEL TERMS TO BE COMPUTED
 M = 50
 K IS THE NUMBER OF DATA POINTS INPUT TO THE PROGRAM
 K = 3
 L IS THE SCREEN TO FIBER DISTANCE IN METERS
 L = .030

DO 19 I=1, K
 READ(5,18) T(I), INTACT(I)
 FORMAT(1X,E17.10,1X,E17.10)
 CONTINUE

PRINT 1
 FORMAT('1')

DO 95 I=1, K
 PRINT, T(I), INTACT(I)
 CONTINUE

THE RESULTS ARE OUTPUT TO THE FOLLOWING DATA FILE

CALL FRTCMS('FILEDEF','08','DISK','RESDAT','DATA',
 *, 'AI'

PROMPT USER FOR INPUT INITIAL GUESS DIAMETER:

```

11 CALL FRTCMS('CLRSCRN ')
12 WRITE(6,12), ' '
13 FORMAT(12), ' '
14 WRITE(6,14)
15 FORMAT(14), ' '
16 READ, DIA
17 WRITE(6,15)
18 FORMAT(15), ' '
19 &MICRONS)
20 READ, ACTUAL
21 DIA = DIA * (1D-06)
22 DEE(1) = DIA
23
24 ECHO INPUT TO THE SCREEN:
25
26 CALL FRTCMS('CLRSCRN ')
27 WRITE(6,16), DEE(1)
28 FORMAT(16), ' '
29 READ, INITIAL_GUESS_DIAMETER_INPUT, IN METERS IS, E12.5)
30 WRITE(6,17), L
31 FORMAT(17), ' '
32 SCREEN TO FIBER DISTANCE IS 'E12.5,' METERS ' '
33
34 RR = 0.0
35 DELTAD = .05E-06
36 BETA = 1E-20
37
38 D = DEE(1)
39 CALL RESID(D, RR, INTACT, INTGES, K, M, T, L)
40 R(1) = RR
41
42 NEWDEL = 0
43 COUNT = 1
44 I = 1
45 FLAG = 1
46 LOWER = 0
47 UPPER = 0
48 TEST = 99
49
50 PRINT, ' '
51 PRINT, ' ', I
52 PRINT, ' ', I
53
54 RESID    DIAMETER    DELTAD    TEST

```

```

C30  WHILE( ABS(TEST) .GT. BETA) DO
C    IF(FLAG .EQ. 1) THEN
C31  DEE(I+1) = DEE(1) + I * DELTAD
C    D = DEE(I+1)
C    CALL RESID(D, RR, INTACT, INTGES, K, M, T, L)
C    R(I+1) = RR
C    UPPER = UPPER + 1
C    END IF
C    IF(FLAG .EQ. 0) THEN
C32  DEE(I+1) = DEE(1) - I * DELTAD
C    D = DEE(I+1)
C    CALL RESID(D, RR, INTACT, INTGES, K, M, T, L)
C    R(I+1) = RR
C    LOWER = LOWER + 1
C    END IF
C    IF(LOWER .EQ. 1) THEN
C    TEST = R(I+1) - R(I-1)
C    ELSE
C    TEST = R(I+1) - R(I)
C    END IF
C    PRINT 62, I, R(I), DEE(I), DELTAD, TEST
C    FORMAT(1X, I2, 1X, E11.4, 1X, E12.5, 1X, E13.5)
C    IF( TEST ) 34, 33, 35
C    GO TO 35
C33

```

```

C34 IF(LOWER .EQ. 0) THEN
C      FLAG = 1
      ELSE
      FLAG = 0
      END IF
      GOTO 36

C35 IF(COUNT .EQ. 1) THEN
C      FLAG = 0
C
      ELSEIF(DELTA.D .EQ. .05E-06) THEN
        DELTA.D = .01E-06
        NEWDEL = 1
        GOTO 38
C
      ELSEIF(DELTA.D .EQ. .01E-06) THEN
        DELTA.D = .005E-06
        NEWDEL = 1
        GOTO 38
C
      ELSEIF(DELTA.D .EQ. .005E-06) THEN
        DELTA.D = .001E-06
        NEWDEL = 1
        GOTO 38
C
      ELSEIF(DELTA.D .EQ. .001E-06) THEN
        DELTA.D = .001E-06
        NEWDEL = 1
        GOTO 38
C
      ELSEIF(DELTA.D .EQ. .001E-06) THEN
        QUIT = 2
      END IF
C
C36 I = I + 1
C38 COUNT = COUNT + 1
C      IF( (NEWDEL .EQ. 1) .AND. (I .GE. 2)) THEN
        DEE{1} = DEE(I-1)
        R{1} = R(I-1)
        I = 1
        NEWDEL = 0
      END IF
C
C

```


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57

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K IS THE NUMBER OF THETA INCREMENTS TO BE CALCULATED/PASSED
 M IS THE NUMBER OF FIRST AND SECOND KIND BESSEL FUNCTIONS
 TO BE CALCULATED
 T IS ARRAY OF THETA VALUES OF K INCREMENTS EVERY .002 RADDS.
 L IS DISTANCE IN METERS FROM THE FIBER TO DIFF PATTERN

```

INTEGER I, N, M, K
REAL DIAM, LAMBDA, L, KNOT, CONST, PI, D, X, J, DIA, T
REAL INTDIF, RR, DD, INTACT, INTGES
DIMENSION J(100), Y(100), R(100), S(100)
& T(100), C(100), RC(100), DENOM(100), DIST(100)
& SSUM(100), INTACT(100), INTDIF(100), INTGES(100), RSUM(100),
  
```

```

PI = 3.141592654
LAMBDA = 632.800D-09
LAMBDA IS THE WAVELENGTH (METERS) OF THE LASER
  
```

DD IS THE ACCURACY PARAMETER FOR THE SUBROUTINE BESJ

```
DD = .000001
```

```

KNOT = (2.0D0 * PI) / LAMBDA
CONST = 2.0D0 / (KNOT * L * PI)
  
```

```
X = (PI * D) / LAMBDA
```

X IS THE VALUE OF ALPHA, THE DIAMETER DEPENDENT ARGUMENT FOR THE BESSEL FUNCTIONS.

GENERATE THE REQUIRED BESSEL FUNCTION VALUES

```

DO 100 I=1,M
N = I-1
IER = 0
  
```

```

CALL BESJ(X,N,BJ,DD,IER)
J(I) = BJ
IERJ(I) = IER
IER = 0
  
```



```

CALL BESY(X,N,BY,IER)
Y(I) = BY
IER(I) = IER
C 100 CONTINUE
*****
GENERATE THE REQUIRED VALUES FOR THETA, SIMILAR TO THOSE
IN THE ACTUAL EXPERIMENT WHERE THETA=ARCTAN(DIST/L). AND
HERE, DISTANCE IS EVERY TWO MILLIMETERS FROM CENTER,
L IS THE SCREEN TO LATH DISTANCE, WHICH IS .5636 METERS.
*****
DO 200 I=1, K
T(I) = I*.602 + .05
200 CONTINUE
*****
CALCULATE THE R(N) AND S(N)
*****
DO 300 I=1, M
DENOM(I) = { J(I) **2 + Y(I) **2 }
R(I) = { J(I) } / DENOM(I)
S(I) = { Y(I) } / DENOM(I)
300 CONTINUE
*****
CALCULATE THE MATRIX OF COSINE VALUES .....
*****
DO 400 I=2, M
DO 399 N=1, K
C(I-1, N) = COS ( (I-1) * T(N) )
400 CONTINUE
399 CONTINUE
*****
GENERATE THE MATRIX OF PRODUCTS
*****

```

```

C      DO 500 I=2, M
C      DO 499 N=1, K
C          RC( I-1, N ) = R(I) * C( I-1, N )
C          SC( I-1, N ) = S(I) * C( I-1, N )
C      CONTINUE
C      CONTINUE
C*****
C      SUM THE COLUMNS IN THE PRODUCT MATRICES .....
C
C      DO 600 N=1, K
C          RSUM(N) = 0
C          SSUM(N) = 0
C          DO 599 I=2, M
C              RSUM(N) = RSUM(N) + RC( I-1, N )
C              SSUM(N) = SSUM(N) + SC( I-1, N )
C          CONTINUE
C          CONTINUE
C      599
C      600
C*****
C      FINAL CALCULATION .....
C
C      DO 700 N=1, K
C          INTGES(N)=CONST*((R(1)+2*RSUM(N))**2 + (S(1)+2*SSUM(N))**2)
C
C      700
C      1000
C      CONTINUE
C      CONTINUE
C*****
C      RESIDUAL SUBROUTINE
C
C      THIS TEST SKIPS ROUTINE IF ONLY CALCULATING INTENSITIES
C      FOR THE ACTUAL DIAMETER:
C      INTACT(I) IS THE INTENSITY ARRAY FROM THE INPUT DATA FILE

```



```

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED
NONE
METHOD
RECURRENCE RELATION TECHNIQUE DESCRIBED BY H. GOLDSTEIN AND
R.M. THALER, RECURRENCE TECHNIQUES FOR THE CALCULATION OF
BESSEL FUNCTIONS, M.T.A.C. V.13, PP.102-108 AND I.A. STEGUN
AND M. ABRAMOWITZ, GENERATION OF BESSEL FUNCTIONS ON HIGH
SPEED COMPUTERS, M.T.A.C., V.11, 1957, PP.255-257
.....
SUBROUTINE BESJ(X,N,BJ,D,IER)
  BJ=.0
  IF(N) 10,20,20
  IER=1
  RETURN
  10 IF(X) 30,30,31
  20 IER=2
  RETURN
  30 IF(X-15.) 32,32,34
  31 NTEST=20.+10.*X-X** 2/3
  32 GO TO 36
  34 NTEST=90.+X/2.
  36 IF(N-NTEST) 40,38,38
  38 IER=4
  RETURN
  40 NI=N+1
  BPREV=.0
  COMPUTE STARTING VALUE OF M
  IF(X-5.) 50,60,60
  50 MA=X+6.
  GO TO 70
  60 MA=1.4*X+60./X
  70 MB=N+IFIX(X)/4+2
  MZERO=MAXO(MA,MB)
  SET UPPER LIMIT OF M
  MMAX=NTEST
  100 DO 190 M=MZERO,MMAX,3
  SET F(M),F(M-1)

```

BESJ 300
 BESJ 310
 BESJ 320
 BESJ 330
 BESJ 340
 BESJ 350
 BESJ 360
 BESJ 370
 BESJ 380
 BESJ 390
 BESJ 400
 BESJ 410
 BESJ 420
 BESJ 430
 BESJ 440
 BESJ 450
 BESJ 460
 BESJ 470
 BESJ 480
 BESJ 490
 BESJ 500
 BESJ 510
 BESJ 520
 BESJ 530
 BESJ 540
 BESJ 550
 BESJ 560
 BESJ 570
 BESJ 580
 BESJ 590
 BESJ 600
 BESJ 610
 BESJ 620
 BESJ 630
 BESJ 640
 BESJ 650
 BESJ 660
 BESJ 670
 BESJ 680
 BESJ 690
 BESJ 700
 BESJ 710
 BESJ 720
 BESJ 730
 BESJ 740
 BESJ 750
 BESJ 760
 BESJ 770

```

      FM1=1.0E-28
      FM=.0
      ALPHA=.0
      IF(M-(M/2)*2)120,110,120
110  JT=-1
120  GO TO 130
130  JT=1
      M2=M-2
      DO 160 K=1,M2
      MK=M-K
      BMK=2.*FLOAT(MK)*FM1/X-FM
      FM=FM1
      IF(MK-N-1)150,140,150
140  BJ=BMK
150  JT=-JT
      S=1+JT
      ALPHA=ALPHA+BMK*S
      BMK=2.*FM1/X-FM
      IF(N)180,170,180
170  BJ=BMK
180  ALPHA=ALPHA+BMK
      BJ=BJ/ALPHA
      IF(ABS(BJ-BPREV)-ABS(D*BJ))200,200,190
190  BPREV=BJ
      IER=3
200  RETURN
      END
      .....
SUBROUTINE BESY
PURPOSE
  COMPUTE THE Y BESSEL FUNCTION FOR A GIVEN ARGUMENT AND ORDER
USAGE
  CALL BESY(X,N,BY,IER)
DESCRIPTION OF PARAMETERS
  X -THE ARGUMENT OF THE Y BESSEL FUNCTION DESIRED
  N -THE ORDER OF THE Y BESSEL FUNCTION DESIRED
  BY -THE RESULTANT Y BESSEL FUNCTION
  IER-RESULTANT ERROR CODE WHERE
      IER=0 NO ERROR
      IER=1 N IS NEGATIVE
      IER=2 X IS NEGATIVE OR ZERO
      IER=3 BY HAS EXCEEDED MAGNITUDE OF 10**70
      .....
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC

```

```

REMARKS
VERY SMALL VALUES OF X MAY CAUSE THE RANGE OF THE LIBRARY
FUNCTION ALOG TO BE EXCEEDED
X MUST BE GREATER THAN ZERO
N MUST BE GREATER THAN OR EQUAL TO ZERO

SUBROUTINES AND FUNCTION SUBPROGRAMS REQUIRED.
NONE

METHOD
RECURRENCE RELATION AND POLYNOMIAL APPROXIMATION TECHNIQUE
AS DESCRIBED BY A. J. M. HITCHCOCK, POLYNOMIAL APPROXIMATIONS
TO BESSEL FUNCTIONS OF ORDER ZERO AND ONE AND RELATED
FUNCTIONS, M. T. A. C. V. 11, 1957 PP. 86-88 AND G. N. WATSON,
A TREATISE ON THE THEORY OF BESSEL FUNCTIONS, CAMBRIDGE
UNIVERSITY PRESS, 1958, P. 62
.....

SUBROUTINE BESY(X,N,BY,IER)
CHECK FOR ERRORS IN N AND X

IF(N)180,10,10
IER=0
IF(X)190,190,20

BRANCH IF X LESS THAN OR EQUAL 4
20 IF(X-4.0)40,40,30

COMPUTE Y0 AND Y1 FOR X GREATER THAN 4

30 T1=4.0/X
T2=T1*T1
P0=(((-.0000037043*T2+.0000173565)*T2-.0000487613)*T2
1 +.00017343)*T2-.001753062)*T2+.3989423
Q0=(((-.0000032312*T2-.0000142078)*T2+.000342468)*T2
1 -.000869791)*T2+.0004564324)*T2-.01246694
P1=(((-.0000042414*T2-.0000200920)*T2+.0000580759)*T2
1 -.000223203)*T2+.002921826)*T2+.3989423
Q1=(((-.0000036594*T2+.00001622)*T2-.0000398708)*T2
1 +.0001064741)*T2-.0006390400)*T2+.03740084
A=2.0/SQRT(X)
B=A*T1
C=X-.7853982
Y0=A*PO*SIN(C)+B*QO*COS(C)
Y1=A*PI

```

BESY 690
 BESY 700
 BESY 710
 BESY 720
 BESY 730
 BESY 740
 BESY 750
 BESY 760
 BESY 770
 BESY 780
 BESY 790
 BESY 800
 BESY 810
 BESY 820
 BESY 830
 BESY 840
 BESY 850
 BESY 860
 BESY 870
 BESY 880
 BESY 890
 BESY 900
 BESY 910
 BESY 920
 BESY 930
 BESY 940
 BESY 950
 BESY 960
 BESY 970
 BESY 980
 BESY 990
 BESY 1000
 BESY 1010
 BESY 1020
 BESY 1030
 BESY 1040
 BESY 1050
 BESY 1060
 BESY 1070
 BESY 1080
 BESY 1090
 BESY 1100
 BESY 1110
 BESY 1120
 BESY 1130
 BESY 1140
 BESY 1150
 BESY 1160

```

C
C
C
Y1=-A*P1*COS(C)+B*Q1*SIN(C)
GO TO 90
    COMPUTE Y0 AND Y1 FOR X LESS THAN OR EQUAL TO 4
40  XX=X/2.
    X2=XX*XX
    T=ALOG(XX)+.5772157
    SUM=0.
    TERM=T
    Y0=T
    DO 70 L=1,15
    IF(L-1)50,60,50
50  SUM=SUM+1./FLOAT(L-1)
60  FL=L
    TS=T-SUM
    TERM=(TERM*(-X2)/FL**2)*(1.-1./(FL*TS))
70  Y0=Y0+TERM
    TERM = XX*(T-.5)
    SUM=0.
    Y1=TERM
    DO 80 L=2,16
    SUM=SUM+1./FLOAT(L-1)
    FL=L
    FL1=FL-1.
    TS=T-SUM
    TERM=(TERM*(-X2)/(FL1*FL))*((TS-.5/FL)/(TS+.5/FL1))
80  Y1=Y1+TERM
    P12=.6366198
    Y0=P12*Y0
    Y1=-P12/X+P12*Y1
    CHECK IF ONLY Y0 OR Y1 IS DESIRED
90  IF(N-1)100,100,130
    RETURN EITHER Y0 OR Y1 AS REQUIRED
100 IF(N)110,120,110
110 BY=Y1
    GO TO 170
120 BY=Y0
    GO TO 170
C
C
C
    PERFORM RECURRENCE OPERATIONS TO FIND YN(X)
130 YA=Y0
    YB=Y1

```

BESY1170
 BESY1180
 BESY1190
 BESY1200
 BESY1210
 BESY1220
 BESY1230
 BESY1240
 BESY1250
 BESY1260
 BESY1270
 BESY1280
 BESY1290
 BESY1300
 BESY1310
 BESY1320
 BESY1330
 BESY1340

140 K=1
 T=FLOAT(2*K)/X
 YC=T*YB-YA
 IF (ABS(YC)-1.OE70)145,145,141
 IER=3
 RETURN
 141 K=K+1
 IF (K-N)150,160,150
 YA=YB
 YB=YC
 GO TO 140
 160 BY=YC
 170 RETURN
 180 IER=1
 RETURN
 190 IER=2
 RETURN
 END
 \$ENTRY

\$JOB

EXPOSURE. THIS PROGRAM TAKES AN EXPOSURE OF INTENSITY RATIOS VERSUS THETA DATA. IT BEGINS BY RECOMMENDING THE OPTIMUM EXPOSURE BY FINDING THE MAXIMUM DERIVATIVES OF THE INTENSITY RATIO VS THETA CURVES. THE INTENSITY RATIOS OF THE CORRESPONDING TO THE MAXIMUM DERIVATIVES ARE AVERAGED AND RECOMMENDED AS A GOOD STARTING POINT FOR EXPOSURE.

THE PROGRAM CALLS THE ATTACHED SUBROUTINES 'DERIV' AND 'RANDOM'. 'DERIV' CALCULATES THE OPTIMUM EXPOSURE AND 'RANDOM' INTRODUCES RANDOM ERROR INTO THE INTENSITY RATIO DATA.

VARIABLE DEFINITIONS:

INT ARRAY OF INTENSITY RATIOS (INPUT ARRAY)
 THLOC ARRAY OF THETA LOCATIONS (INPUT ARRAY)
 DESINT ARRAY OF DIGITIZED INTENSITY VALUES
 DESINT DESIRED INTENSITY RATIO (EXPOSURE VALUE)
 THE 'INT' ARRAY IS DIGITIZED WITH RESPECT TO THE VALUE OF 'DESINT'

INTAVG THE AVERAGE VALUE OF THE MAX DERIVATIVE INTENSITIES
 'INTAVG' IS RETURNED FROM THE SUBROUTINE 'SLOPE'

THLOC ARRAY OF THETA LOCATIONS CORRESPONDING TO THE PROGRAM LOCATED INTENSITY RATIOS. (I.E. DESINT)

ERR VALUE OF ERROR TO BE INTRODUCED IN THE RANDOM SUBROUTINE. EXAMPLE: 1% ERROR INPUT AS .01.

INTERR ARRAY OF INTENSITY RATIOS RETURNED FROM THE SUBROUTINE 'RANDOM'.

GUTINT GOOD INTENSITY RATIOS

FLAG SEARCH FLAG USED DURING DIGITIZATION
 EFLAG FLAG TO INDICATE IF ERROR HAS BEEN INTRODUCED INTO DATA
 ERROR FLAG INDICATING USER DESIRE TO CALL 'RANDOM' SUBROUTINE
 DEFAULT FLAG INDICATING USER DESIRE TO KEEP RECOMMENDED SEARCH INTENSITY VALUE, OR SELECT ANOTHER.

INTEGER DIGINT, FLAG, FFLAG, ERROR, DEFAULT, KNOW, IX
 INTEGER Z, M, SUM, LL, VG, FE, BB, KK, CC, RS
 REAL INT, T, NEWINT, THLOC, DESINT, INTAVG, ERR, INTB
 REAL INTERR, GUDINT, DIAMTR, ANYNUM, AA, TAVG, DIFF


```

C      CALL SLOPE(T, INT, K, GUDINT, NO, DESINT, DIAMTR)
C
C      CALL ERTCMS('CLRSCRN ')
C
100    WRITE(6, 100) DESINT
      FORMAT(1X, 'BASED ON THE MAXIMUM INTENSITY DERIVATIVES THE',
&/, 1X, 'SUBROUTINE SLOPE RECOMMENDS THE FOLLOWING INTENSITY',
&/, 1X, 'RATIO FOR AN OPTIMUM EXPOSURE: E17.10/1X',
& 'THIS VALUE IS THE AVERAGE OF THE FOLLOWING INTENSITY RATIOS: ')
C
      DO 110 I=1, NO
      WRITE(6, 109) GUDINT(I)
109    FORMAT(1X, E17.10, /)
110    CONTINUE
C
120    WRITE(6, 120)
      FORMAT(1X, 'DO YOU DESIRE TO SELECT ONE OF THE ABOVE INTENSITY',
& RATIOS, /, 1X, 'IF NOT THE RECOMMENDED VALUE IS THE DEFAULT',
& VALUE. /, 1X, 'ENTER 1=YES, 0=NO')
      READ, DEFALT
C
130    IF(DEFAULT.EQ. 1) THEN
      WRITE(6, 130) 'INPUT THE DESIRED INTENSITY VALUE'
      READ, DESINT
      END IF
C
C      CALL ERTCMS('CLRSCRN ')
C
      EFLAG = 0
140    WRITE(6, 140)
      FORMAT(1X, 'DO YOU DESIRE TO SIMULATE ERROR? 1=YES, 0=NO')
      READ, ERROR
C
      IF(ERROR.EQ. 1) THEN
150    WRITE(6, 150)
      FORMAT(1X, 'INPUT THE DESIRED ERROR (I.E. INPUT 1% AS .01)')
      READ, ERR
C
      WRITE(6, 151)
151    FORMAT(1X, 'INPUT ODD INTEGER LESS THAN 99999 TO SEED GENERATOR')
      READ, IX
C
C      CALL ERTCMS('CLRSCRN ')
C
      CALL RANDOM(T, INT, INTERR, ERR, K, DIAMTR, IX)
      EFLAG = 1

```

```

C
END IF
IF(EFLAG.EQ. 1) THEN
DO 160 I=1,K
INT(I) = INTERR(I)
CONTINUE
END IF
160
C
DO 20 I=1,K
IF ( INT(I) .GE. DESINT ) THEN
DIGINT(I) = 0
ELSE
DIGINT(I) = 1
END IF
CONTINUE
20
C
IF(DIGINT(1) .EQ. 0) THEN
FLAG = 0
ELSE
FLAG = 1
END IF
C
L = 1
J = K-1
DO 30 I=1, J
IF( FLAG.EQ. 0) .AND. (DIGINT(I) .EQ. 0) ) GO TO 30
IF( FLAG.EQ. 1) .AND. (DIGINT(I) .EQ. 1) ) GO TO 30
IF( FLAG.EQ. 0) .AND. (DIGINT(I) .EQ. 1) ) THEN
THLOC(L) = ( T(I) + T(I-1) ) / 2
L = L + 1
FLAG = 1
GO TO 30
END IF
C
IF( FLAG.EQ. 1) .AND. (DIGINT(I) .EQ. 0) ) THEN
THLOC(L) = ( T(I) + T(I-1) ) / 2
L = L + 1
FLAG = 0
GO TO 30
END IF

```

```

C 30      CONTINUE
C
C 35      IF(KNOW .EQ. 1) THEN
C          WRITE(8,35) DIAMTR
C          FORMAT(1X,'FOR A DIAMETER = ',F8.5,' MICRONS',/)
C          ELSE
C 36      WRITE(8,36)
C          FORMAT(1X,' DIAMETER UNKNOWN ..... ',/)
C          END IF
C
C 38      WRITE(8,38) THETA', 10X, 'INTENSITY', 8X, 'DIGITAL INTENSITY',/
C          FORMAT(4X, THETA', 10X, 'INTENSITY', 8X, 'DIGITAL INTENSITY',/
C
C 40      DO 41 I=1, J
C 41      WRITE(8,40) T(I), INT(I), DIGINT(I)
C          FORMAT(1X,E17.10, 1X,E17.10, 1X,I2)
C          CONTINUE
C
C 45      WRITE(8,45) DESINT
C          FORMAT(/, 'THE THETA LOCATIONS FOR THE DESIRED INTENSITY',
C          &E17.10, ' ARE: ',/)
C
C 47      WRITE(8,47) THETA LOCATION', 4X, 'DESIRED INTENSITY',/
C          FORMAT(1X, THETA LOCATION', 4X, 'DESIRED INTENSITY',/
C
C          M = L - 1
C
C 50      DO 51 I=1, M
C 51      WRITE(8,50) THLOC(I), DESINT
C          FORMAT(1X,E17.10, 1X,E17.10)
C          CONTINUE
C
C          THE FOLLOWING ROUTINE FINDS THETA LOCATIONS WHICH ARE
C          LOCATED NEAR EACH OTHER. THESE COLOCATED POINTS ARE
C          AVERAGED AND ASSIGNED THE NAME 'TAVG' THEN THE TAVG
C          IS OUTPUT TO THE DATA FILE 'EXP WATFIV A1' FOR USE BY
C          THE DIAMETER FINDING PROGRAMS. (TAVG IS ALSO OUTPUT TO
C          TO THE DATA FILE 'DIGITAL DATA'.)
C
C          Z = M-1
C          SUM = 0
C          LL = 1
C

```

```

DO 54 I=1, Z
DIFF = ABS( THLOC(I+1) - THLOC(I) )
IF(DIFF .LE. 1.005) THEN
SUM = SUM + 1
ELSE
AVG(LL) = SUM + 1
LL = LL + 1
SUM = 0
END IF
CONTINUE
AVG(LL) = SUM + 1

54 C
MM = LL
BB = 0
DO 57 I=1, MM
FF = AVG(I)
AA = 0.0
DO 56 II=1, FF
AA = AA + THLOC(II + BB)
CONTINUE
BB = BB + FF
TAVG(I) = AA / FF
CONTINUE

56 C
57 C
DO 61 I=1, MM
IF(I.GT.3) GOTO 61
WRITE(9,60) TAVG(I), DESINT
FORMAT(1X,E17.10, 1X,E17.10)
CONTINUE

60 C
61 C
WRITE(8,70) THETA LOCATION', 4X,'DESIRED INTENSITY',/)
FORMAT(1X,

DO 72 I=1, MM
WRITE(8,71) TAVG(I), DESINT
FORMAT(1X,E17.10, 1X,E17.10)
CONTINUE

71 C
72 C
WRITE(8,73) M, Z, LL, MM, FF, SUM, DIFF
FORMAT(1X,M=,Z=,LL=,MM=,FF=,SUM=,DIFF=,
&F7.4,/,/)

73 C
STOP
END
C
C

```

```

*****
SUBROUTINE SLOPE
*****
*****

```

```

SUBROUTINE SLOPE(T, INT, K, GUDINT, NO, INTAVG, DIAMTR)

THIS SUBROUTINE CALCULATES THE SLOPES OF A GIVEN INTENSITY
CURVE. THE ROUTINE FINDS AND RETURNS THE VALUES OF THE MAXIMUM
DERIVATIVES, NAMED "GOODINT". ALSO RETURNED IS THE AVERAGE OF
THE GOODINT VALUES, "INTAVG".

```

```

INT      = VALUES OF INTENSITY RATIOS FROM CALLING PROGRAM
K        = NUMBER OF VALUES PASSED FROM CALLING PROGRAM
GUDINT   = VALUES OF THE MAXIMUM DERIVATIVES
NO       = INTEGER NUMBER OF GOODINT VALUES
INTAVG   = AVERAGE OF GOODINT VALUES ('DESIRED INTENSITY')

```

```

INTEGER J, K, L, NO
REAL T(400), INT(400), DER(400), DERIV(400), GUDINT(400)
REAL INTAVG, A, DIAMTR

```

```

CALL FRTCMS('FILEDEF ', '11', 'DISK', 'DERIV', 'DATA',
*, 'A1'

```

```

L = K-1
DO 25 I=1, L
  INT(I+1) = INT(I) / ( T(I+1) - T(I) )
  DER(I) = ABS( DER(I) )
CONTINUE

```

```

J = 1
M = K-3
DO 50 I=1, M

```

25

```

50 IF((DERIV(I+1).GT.DERIV(I)).AND.(DERIV(I+1).GT.DERIV(I+2)))THEN
   GUDINT(J) = INT(I+1)
   J = J+1
   END IF
   CONTINUE
   NO = J-1
   C
   C
51 A = 0.0
   DO 51 I=1, NO
     A = A + GUDINT(I)
     CONTINUE
     INTAVG = A / NO
     C
     C
     C
     C
     C
     C
     C
73 IF(DIAMTR.NE.0.0) THEN
   WRITE(11,73) DIAMTR
   FORMAT(1X,73) FIBER DIAMETER = ',F7.4,' MICRONS',/)
   ELSE
74 WRITE(11,74)
   FORMAT(1X,74) FIBER DIAMETER UNKNOWN',/)
   END IF
   C
98 WRITE(11,98) THETA',12X,'DERIVATIVE',/)
   FORMAT(3X,12X,'DERIVATIVE',/)
   C
99 DO 100 I=1,M
100 WRITE(11,99) T(I), DERIV(I)
   FORMAT(1X,E17.10,1X,E17.10)
   CONTINUE
   C
150 WRITE(11,150) INTAVG
   FORMAT('/',1X,THE AVERAGE OPTIMUM INTENSITY IS: ',E17.10,/,
   &' AND THE INDIVIDUAL INTENSITIES ARE: ',/)
   C
   C
   C
200 DO 200 I=1,NO
   WRITE(11,199) GUDINT(I)
   FORMAT(1X,E17.10)
   CONTINUE
   C

```



```

000000 SEARCH INTENSITY RATIO FILE FOR THE MAXIMUM VALUE OF THE
        INTENSITY RATIO. NAME THIS VALUE 'MAXINT' AND ITS
        CORRESPONDING THETA LOCATION 'THMAX'.

        M = K-1
        MAXINT = INT(1)
        THMAX = T(1)

        DO 01 I=1, M
        IF (INT(I+1) .GT. MAXINT) THEN
        MAXINT = INT(I+1)
        THMAX = T(I+1)
        END IF
        CONTINUE

01
000000 CALCULATE THE RANDOM NUMBERS USING NONIMSL SUBROUTINE 'RANDU'

        DO 12 I=1, K
        CALL RANDU(IX, IY, YEL)
        IX = IY
        RAN(I) = YEL
        CONTINUE

12
000000 CHANGE THE RANDOM NUMBER RANGE FROM (0 TO +1) TO (-1 TO +1)

        DO 13 I=1, K
        IF (RAN(I) .GT. .5) THEN
        RANPM1(I) = 2 * ( RAN(I) - .5)
        ELSE
        RANPM1(I) = (-2) * ( RAN(I))
        END IF
        CONTINUE

13
000000 CALCULATE THE NEW INTENSITY ARRAY WITH THE INTRODUCED ERROR.
        NOTE THAT ERROR IS BASED UPON MAXIMUM INTENSITY (WHICH WAS
        FOUND ABOVE: 'MAXINT' AND 'THMAX')

        DO 15 I = 1, K
        INTERR(I) = 1, INT(I) + (MAXINT * ERR * RANPM1(I))
        CONTINUE

15

```

```

C
C
C      OUTPUT THE ARRAY .....
      IF(DIAMTR.NE. 0.0) THEN
        WRITE(4,73) DIAMTR
        FORMAT(1X,FIBER DIAMETER = ', F7.4, ' MICRONS',/)
      ELSE
        WRITE(4,74)
        FORMAT(1X,FIBER DIAMETER UNKNOWN',/)
      END IF
C
C      WRITE(4,75) THMAX, MAXINT, ERR
      FORMAT(1X,MAX INTENSITY,RATIO OCCURS AT THETA = ', E17.10,/,
      &1X,'AND HAS MAGNITUDE = ', E17.10,/,/, 1X, INPUT ERROR = ',
      &E5.3, //)
C
C      WRITE(4,76) 'THETA', 11X, 'INTENSITY', 9X, 'INT. W/ERROR',//)
      FORMAT(4X,
C
      DO 100 I=1,K
        WRITE(4,99) T(I), INT(I), INTERR(I)
        FORMAT(1X,E17.10, 1X,E17.10, 1X,E17.10)
      CONTINUE
      100
C
      RETURN
      END
C*****
C      END OF SUBROUTINE RANDOM
C*****
C$ENTRY

```

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